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A study on the synergy of manufacturing development in the Nanjing Metropolitan Area based on the entropy weight method: assessment and empirical analysis

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Abstract. This study focuses on eight cities within the Nanjing Metropolitan Area (NMA) and takes the manufacturing industry of the NMA as the research object. Using data from 2015 to 2020, we apply the orderliness model and the coupling coordination model. Ten manufacturing sectors within the NMA are selected, and a two-level evaluation index system for the NMA's manufacturing industry is established to measure the development level of the sector and to explore its development trends. The results indicate that high-level advantageous industries overlap among the cities in the NMA; the external orderliness of the metropolitan manufacturing sector exhibits heterogeneity in the secondary subsystem; and the coupling and coordination among the manufacturing industries of the cities within the metropolitan area show relatively small differences. Based on these findings and the functional positioning of the eight cities, targeted recommendations are proposed for the future development of the NMA's manufacturing industry.

Keywords: Nanjing Metropolitan Area, manufacturing industry, orderliness, coupling coordination degree, location quotient

1. Introduction

The manufacturing industry is the foundation of national strength and the cornerstone of a strong country. Currently, China is in a new era of urbanization, and the Nanjing Metropolitan Area (NMA) has a solid manufacturing base, playing a crucial role in regional economic development. Therefore, promoting the coordinated development of the manufacturing sector is of great significance for enhancing the overall competitiveness of the NMA. At present, the NMA has achieved certain progress in industrial division of labor, yet challenges remain, such as insufficient coordination and uneven distribution of innovation resources. In 2024, the Ministry of Industry and Information Technology issued the Guiding Opinions on Accelerating the Green Development of Manufacturing, emphasizing the need to promote differentiated transformation of traditional industries and to implement major regional strategic positioning. This highlights that the implementation of major regional strategies by cities in the NMA can strengthen intercity industrial division of labor and collaboration, thereby improving overall competitiveness.

From the perspective of metropolitan areas, China is currently undergoing new urbanization. A metropolitan area is composed of a central super-large or large city with strong radiation and driving functions, connected to surrounding regions with close socio-economic linkages. It serves as an important carrier for supporting urban cluster economic growth and promoting regional development, which is vital for advancing modern urbanization. Furthermore, in 2021, China approved the Nanjing Metropolitan Area Development Plan. As the first nationally approved metropolitan area plan, the NMA spans Jiangsu and Anhui provinces and is the first cross-provincial metropolitan area in China, marking a new strategic stage in its development. In 2023, the Jiangsu Provincial Government approved the Overall Land and Space Planning for Danyang, Yangzhong, and Jurong (2021–2035), which highlights Jurong as a new hub for advanced manufacturing within the NMA and a pilot zone for Ning-Zhen-Yang integration. This reflects the provincial-level positioning and guidance for the manufacturing development of cities within the NMA.

From the perspective of the manufacturing sector, as General Secretary Xi Jinping stated, "The manufacturing industry is the foundation of the real economy; the real economy is the capital for China's development and an important support for building strategic advantages in future development." This indicates that the level of manufacturing integration constrains the high-quality development of metropolitan areas, and the manufacturing sector continues to play an extremely important role in economic growth. In the industrial development of the NMA, manufacturing has historically been both a key focus and a challenge.

Although the 2024 List of Major Economic and Social Development Projects in Nanjing is not a policy document specifically targeting the NMA's manufacturing sector, the allocation of major projects significantly impacts its development. For instance, advanced manufacturing projects occupy a substantial proportion of Nanjing's 2024 major projects, with manufacturing development designated as a core task. This will drive overall development of manufacturing in the NMA and promote industrial upgrading and innovation.

This study takes industrial synergy within the manufacturing sector as the entry point, focusing on the NMA. Based on a manufacturing evaluation system, it uses location quotient, orderliness, and coupling coordination models to measure and analyze the advantageous industries and overall development of manufacturing in the NMA from 2015 to 2020. It aims to explore the development potential of each city's manufacturing system, strengthen the coupling and comprehensive analysis of manufacturing across urban systems, and provide theoretical and practical references for formulating policies and enhancing the competitiveness of manufacturing hubs. The innovations of this study are threefold: first, using location quotient analysis to identify advantageous industries in each city's manufacturing sector; second, using orderliness analysis to assess industrial synergy within the metropolitan area; third, using coupling coordination analysis to reveal the dynamic relationships of interdependence, coordination, and mutual promotion among cities in the NMA.

2. Literature review

In recent years, under the background of global economic integration, the manufacturing industry, as a pillar of the national economy, has attracted extensive attention. Its development and transformation not only affect the sustained growth of national economies but also profoundly influence environmental sustainability and industrial development. Domestic and international scholars have conducted extensive and in-depth studies on the current status, measurement methods, and future trends of the manufacturing sector. This study analyzes the development status of advantageous manufacturing industries in each city of the Nanjing Metropolitan Area (NMA) using the location quotient model, and empirically examines the development of manufacturing in these cities through methods such as orderliness and coupling coordination. Therefore, this chapter reviews relevant literature on manufacturing research and measurement methods by domestic and foreign scholars and summarizes the development level of the NMA's manufacturing sector.

Regarding studies on manufacturing by domestic and international scholars, Yongqiang Yin and Zhenxiao Xu primarily approached the topic from the perspectives of regional economic integration and industrial agglomeration. Their research focused on the coupling and coordination effects between economic development and environmental protection in the Yangtze River Delta urban agglomeration, revealing the interaction between manufacturing development and environmental conservation in developed regions, and highlighting the importance of coordinated governance during industrial agglomeration in the process of regional economic integration [1]. Kai Zhu and Wanxiang Sun further explored the level of collaborative agglomeration and spatial correlation of manufacturing among cities in the Yangtze River Delta, providing empirical support for coordinated regional manufacturing development [2]. Wang Zengyang and colleagues, in their study on the NMA, pointed out that manufacturing and producer services exhibit coordinated agglomeration in spatial distribution, which not only promotes efficient allocation of resources but also enhances regional economic competitiveness [3]. Similarly, Wen Qing and Ma Haixia analyzed the level of industrial coordination in the Urumqi Metropolitan Area, highlighting both the necessity and potential for coordinated development [4]. Jiajun Zhang and colleagues focused on manufacturing transformation, upgrading, and green development. Their research emphasized the coordinated development of new-type productivity and manufacturing carbon emission efficiency across China's provinces, noting that promoting high-quality manufacturing development must be accompanied by energy conservation and emission reduction to achieve green transformation [5]. Peng Zeng and others examined the coupling coordination of urban agglomerations in China from the perspective of urbanization and ecological security, offering new ideas for sustainable manufacturing development [6]. Liu Kang and Liu Xiaoying studied the spatial spillover effects of industrial coordinated agglomeration on new-type urbanization, indirectly reflecting the positive impact of manufacturing transformation and upgrading on regional socio-economic development [7]. The development of manufacturing is often accompanied by the expansion of urban built-up areas and changes in land use. Wang Yiwen and colleagues, using big data on industrial development, analyzed the spatiotemporal characteristics of urban expansion in the NMA, revealing the impact of manufacturing expansion on urban spatial structure [8]. Xu Hao and others examined changes in regional green space in the NMA over the past 15 years, providing references for balancing manufacturing development and environmental protection [9]. Javier Revilla Diez focused on manufacturing innovation networks and internationalization strategies. Through a study of the manufacturing innovation network in the Barcelona metropolitan area, he revealed the crucial role of innovation networks in promoting technological progress and industrial upgrading [10]. Yuri Simachev and colleagues explored research opportunities for sustainable supply chains in the context of Pharma Industry 4.0, emphasizing the importance of smart manufacturing technologies in driving transformation and upgrading in the pharmaceutical sector [11].

In exploring methods for measuring the manufacturing sector, it has been found that when assessing the relationship between manufacturing and related factors (such as the economy, environment, and urbanization), coupling coordination analysis has become an important approach. Studies by Yongqiang Yin, Zhenxiao Xu, and Peng Zeng have employed this method by constructing coupling coordination models to quantitatively analyze the interactions between different systems, providing scientific support for policy formulation. Jiajun Zhang and colleagues introduced a coordinated development assessment model, comprehensively considering both new-type productivity and manufacturing carbon emission efficiency to evaluate the development quality of manufacturing across provinces. This method not only emphasizes improvements in individual indicators but also focuses on the coordinated development of the entire system, providing an evaluation framework for high-quality manufacturing development. Empirical research methods have also been widely used. Kai Zhu, Wanxiang Sun, and Nelson Oly Ndubisi conducted in-depth investigations of specific regions or enterprises, revealing the intrinsic patterns and external influencing factors of manufacturing development. Ching-Hung Lee and colleagues applied bibliometric analysis and topic modeling to systematically review and predict trends in the digital transformation of advanced manufacturing and engineering fields. Regarding the spatial distribution and coordinated agglomeration of manufacturing, Wang Zengyang and colleagues constructed spatial distribution models to quantify the degree of coordinated agglomeration between manufacturing and producer services, providing scientific evidence for regional industrial policy formulation. Similar methods can be applied to analyze coordinated agglomeration in other regions or industries. Wen Qing and Ma Haixia employed orderliness and composite system coordination models to measure the level of industrial coordination in the Urumqi Metropolitan Area, offering quantitative evaluation tools for regional coordinated development. This approach is applicable not only at the metropolitan area level but can also be extended to broader regional and industrial contexts. Wang Yiwen, through mining industrial development big data, revealed the spatiotemporal characteristics of urban expansion in the NMA, providing data support for spatial planning in manufacturing development.

In examining the development of manufacturing in the NMA, Wenjing Ge not only reviewed the historical evolution of the metropolitan area but also prospectively outlined its future development, emphasizing the importance of enhancing overall strength and competitiveness [12]. This perspective provides a macro-strategic foundation for studying industrial synergy and highlights the core role of manufacturing in the economic integration of the NMA. Xu Hao and colleagues, through empirical analysis, revealed the intrinsic connection between regional green space changes and economic development. They found that although green space has decreased, policy interventions and increased ecological awareness are gradually mitigating this trend. This finding underscores the need to consider environmental carrying capacity when promoting coordinated manufacturing development to achieve a win-win outcome for economic growth and environmental protection. Regional development reports by DaGui Cao and others provide updates on economic cooperation in the NMA [13], indicating that with deepening regional collaboration, the NMA is progressively entering a stage of comprehensive and diversified cooperation. This trend offers ample opportunities for coordinated manufacturing development, especially through optimizing industrial layouts, leveraging innovation advantages, and promoting interconnected transportation infrastructure. Fangying Chen conducted an in-depth analysis of industrial structure within the NMA, using location quotient and grey relational analysis to verify the complementarity of intercity industrial structures and to identify the potential for coordinated development between manufacturing and producer services [14]. This provides strong empirical support for studies on industrial synergy and serves as a reference for formulating specific coordination strategies. Finally, Shouhua Wei and Feifei Qian analyzed the development status and challenges of the NMA from the perspective of economic integration [15]. They examined hard factors such as economic development levels, industrial structure evolution, and transportation infrastructure, as well as soft factors including innovation capacity and healthcare and education. This comprehensive perspective provides an important reference for understanding the background and context of coordinated manufacturing development in the NMA.

In summary, existing studies have several limitations. First, from the research perspective, industrial coordination refers to the synergy of different industries within a specific spatial context, possessing a dual “industry-space” attribute. However, some studies focus primarily on spatial attributes [16] while neglecting the degree of industrial coordination. Second, in terms of research subjects, most studies on coordination focus on regions or provinces, with relatively few examining metropolitan area-level industrial coordination. Third, regarding research content, existing studies primarily concentrate on coordination between manufacturing and producer services or other industries [17], while research on coordination among different industries within manufacturing remains relatively scarce. Therefore, this study analyzes the development status of advantageous manufacturing industries in each city of the NMA using the location quotient model, and applies orderliness and coupling coordination methods to empirically examine the development of manufacturing in these cities, providing insights for enhancing the overall level of manufacturing development in the NMA.

3. Distribution of advantageous industries

3.1. Location quotient

The location quotient (LQ), also known as the specialization rate or regional scale advantage index, reflects the advantage and competitiveness of a particular industry. It is commonly used to measure the degree of industrial agglomeration and specialization. In this study, the location quotient is employed to analyze the coordinated development of manufacturing in the Nanjing Metropolitan Area (NMA). The formula is as follows:

$$\lambda=\frac{q_{ij}}{q_j}/\frac{q_i}{q} \tag{1}$$

In formula (1), q_{ij} represents the output value of industry i in region j, q_j represents the total output value of region j, q_i represents the output value of industry i in the NMA, and q represents the total output value of the NMA. If $\lambda > 1$, it indicates that the specialization level of industry i in region j is higher than the average level of the NMA. Therefore, industry i in region j can be considered to have strong agglomeration capacity and is regarded as an advantageous industry. Conversely, the specialization level is relatively low, the agglomeration capacity is weak, and the industry is not considered advantageous.

3.2. Advantageous industries

According to the criteria for identifying advantageous industries, the Nanjing Metropolitan Area (NMA) exhibits the following patterns: Nanjing's advantageous industries (location quotient LQ > 1) include pharmaceutical manufacturing, general equipment manufacturing, railway manufacturing, automobile manufacturing, computer-related industries, chemical products manufacturing, and non-metallic mineral products, totaling seven industries. Zhenjiang's advantageous manufacturing industries comprise pharmaceutical manufacturing, general equipment manufacturing, railway manufacturing, petroleum and fuel processing, automobile manufacturing, computer-related industries, chemical products manufacturing, black metal processing, non-metallic mineral products, and electrical machinery, totaling ten industries. Yangzhou's advantageous industries include general equipment manufacturing, petroleum and fuel processing, automobile manufacturing, chemical products manufacturing, and non-metallic mineral products, totaling five industries. Huai'an's advantageous industries comprise general equipment manufacturing, computer-related industries, chemical products manufacturing, black metal processing, non-metallic mineral products, and electrical machinery, totaling six industries. Wuhu's advantageous industries include general equipment manufacturing, petroleum and fuel processing, automobile manufacturing, chemical products manufacturing, black metal processing, and non-metallic mineral products, totaling six industries. Ma'anshan's advantageous industries include railway manufacturing, petroleum and fuel processing, computer-related industries, and non-metallic mineral products, totaling four industries. Chuzhou's advantageous industries comprise general equipment manufacturing, automobile manufacturing, computer-related industries, chemical products manufacturing, non-metallic mineral products, and electrical machinery, totaling six industries. Xuancheng's advantageous industries include general equipment manufacturing, railway manufacturing, automobile manufacturing, black metal processing, non-metallic mineral products, and electrical machinery, totaling six industries. These variations in advantageous industries across cities provide a foundation for the overall development of manufacturing within the NMA. Therefore, the following analysis constructs an evaluation index system for manufacturing development and applies both the orderly degree model and the coupling coordination model to empirically examine the development level of the NMA's manufacturing sector from both intra-industry and inter-industry perspectives. The specific location quotient indices are presented in Table 1.

Table 1. Regional location entropy index of manufacturing industry in Nanjing Metropolitan Area

City	industry	2015	2016	2017	2018	2019	2020
Nanjing	Chemical products industry	0.605	0.668	1.230	0.234	2.314	2.611
	Automobile manufacturing industry	1.687	1.726	2.687	0.228	2.085	2.152
	Computer industry	4.295	4.034	5.960	0.745	6.899	6.044
	Electrical machinery industry	0.589	0.499	0.299	0.099	1.396	1.454
	Black gold processing industry	0.547	0.510	0.486	0.092	1.004	1.037
	Petroleum fuel industry	0.371	0.340	0.489	0.107	1.574	1.735
	General manufacturing industry	3.445	3.087	4.151	0.373	3.288	2.397
	Non-metal products industry	4.027	3.937	3.577	0.519	6.003	6.797
	Pharmaceutical products industry	0.613	0.615	0.697	1.905	2.020	1.830
	Railway manufacturing industry	2.497	2.447	1.835	0.286	4.630	7.120

Zhenjiang	Chemical products industry	1.000	0.950	1.206	0.274	2.387	2.417
	Automobile manufacturing industry	1.000	0.950	1.205	0.274	2.388	2.418
	Computer industry	0.999	0.949	1.204	0.274	2.385	2.415
	Electrical machinery industry	1.000	0.950	1.206	0.274	2.388	2.417
	Black gold processing industry	1.000	0.951	1.206	0.274	2.389	2.418
	Petroleum fuel industry	0.999	0.950	1.206	0.274	2.387	2.418
	General manufacturing industry	0.999	0.949	1.205	0.274	2.387	2.417
	Non-metal products industry	0.998	0.948	1.203	0.274	2.380	2.408
	Pharmaceutical products industry	1.001	1.001	1.000	0.274	2.389	2.419
	Railway manufacturing industry	1.000	1.000	1.000	1.001	0.999	0.998
Yangzhou	Chemical products industry	0.902	1.116	2.220	0.304	2.487	2.420
	Automobile manufacturing industry	1.509	1.686	2.670	0.628	2.286	2.347
	Computer industry	0.201	0.184	0.284	0.036	0.592	0.645
	Electrical machinery industry	0.726	0.491	0.428	0.091	1.499	1.907
	Black gold processing industry	0.541	0.495	0.639	0.106	1.094	1.461
	Petroleum fuel industry	1.209	1.158	1.476	0.247	3.495	2.978
	General manufacturing industry	3.954	3.241	4.128	0.316	4.412	4.389
	Non-metal products industry	2.845	2.616	3.140	0.222	3.304	4.614
	Pharmaceutical products industry	0.610	0.557	0.625	1.008	1.238	1.091
	Railway manufacturing industry	0.762	0.793	0.552	0.093	1.692	1.810
Huaian	Chemical products industry	1.630	1.769	3.895	0.740	8.094	8.260
	Automobile manufacturing industry	1.207	1.338	1.358	0.097	0.887	0.805
	Computer industry	13.657	13.411	15.797	2.197	9.059	13.563
	Electrical machinery industry	1.937	1.677	1.675	0.502	5.335	6.378
	Black gold processing industry	1.489	1.254	1.396	0.217	2.897	3.891
	Petroleum fuel industry	0.096	0.094	0.173	0.042	0.819	0.931
	General manufacturing industry	2.219	1.910	2.567	0.220	2.794	0.880
	Non-metal products industry	12.689	13.591	15.793	1.831	25.838	27.309
	Pharmaceutical products industry	0.072	0.084	0.094	0.164	0.275	0.355
	Railway manufacturing industry	0.081	0.072	0.145	0.008	0.098	0.029
Wuhu	Chemical products industry	1.328	1.261	2.758	0.420	4.047	3.966
	Automobile manufacturing industry	3.435	2.846	2.610	0.207	1.695	1.735
	Computer industry	0.033	0.030	0.041	0.004	0.096	0.107
	Electrical machinery industry	0.251	0.234	0.170	0.056	0.400	0.646
	Black gold processing industry	1.526	1.300	1.465	0.298	2.766	3.113
	Petroleum fuel industry	1.138	1.042	1.642	0.243	3.030	2.778
	General manufacturing industry	5.174	4.957	5.515	0.603	7.056	6.294
	Non-metal products industry	2.013	2.119	2.527	0.438	2.682	3.150
	Pharmaceutical products industry	0.116	0.119	0.135	0.377	0.388	0.383
	Railway manufacturing industry	0.547	0.710	0.844	0.139	1.725	1.628
Maanshan	Chemical products industry	0.031	0.036	0.511	0.043	0.937	1.367
	Automobile manufacturing industry	0.031	0.047	0.303	0.019	0.132	0.445
	Computer industry	0.177	0.180	1.762	0.119	1.556	3.286
	Electrical machinery industry	0.006	0.016	0.107	0.033	0.354	0.700
	Black gold processing industry	0.069	0.069	0.027	0.002	0.032	0.062
	Petroleum fuel industry	3.519	3.213	2.543	0.517	6.060	0.750
	General manufacturing industry	0.138	0.126	0.834	0.071	0.935	1.563
	Non-metal products industry	1.528	1.607	9.352	0.699	10.639	23.181
	Pharmaceutical products industry	0.013	0.017	0.102	0.261	0.324	0.541
	Railway manufacturing industry	0.463	0.446	3.138	0.580	9.351	19.043

Chuzhou	Chemical products industry	1.522	1.565	3.470	0.775	6.638	7.072
	Automobile manufacturing industry	2.318	3.125	3.167	0.279	1.107	1.143
	Computer industry	5.423	5.409	8.075	1.069	11.909	16.183
	Electrical machinery industry	5.623	5.523	4.808	1.179	11.518	13.113
	Black gold processing industry	0.449	0.073	0.244	0.050	0.506	0.327
	Petroleum fuel industry	0.009	0.008	0.012	0.001	0.013	0.014
	General manufacturing industry	1.458	1.065	1.268	0.132	1.455	0.816
	Non-metal products industry	17.439	16.683	16.518	2.851	38.079	38.927
	Pharmaceutical products industry	0.042	0.037	0.026	0.058	0.077	0.110
	Railway manufacturing industry	0.139	0.152	0.110	0.028	0.451	0.694
Xuancheng	Chemical products industry	0.146	0.108	0.040	0.009	0.034	0.025
	Automobile manufacturing industry	4.046	5.002	8.434	0.507	4.217	6.262
	Computer industry	1.031	0.905	1.411	0.136	1.077	1.369
	Electrical machinery industry	1.371	1.299	1.065	0.409	5.102	4.758
	Black gold processing industry	3.091	3.016	3.110	0.488	3.689	2.985
	Petroleum fuel industry	0.243	0.185	0.294	0.077	0.942	0.715
	General manufacturing industry	3.192	2.354	1.306	0.140	1.556	1.172
	Non-metal products industry	8.981	9.027	10.291	1.428	14.480	17.120
	Pharmaceutical products industry	0.316	0.323	0.275	0.735	1.024	1.000
	Railway manufacturing industry	1.350	1.333	1.599	0.307	5.738	6.435
Nanjing metropolitan area	Chemical products industry	0.48	0.48	0.23	0.10	0.21	0.13
	Automobile manufacturing industry	0.08	0.09	0.14	0.41	0.15	0.16
	Computer industry	0.10	0.10	0.12	0.08	0.11	0.14
	Electrical machinery industry	0.14	0.14	0.20	0.15	0.16	0.17
	Black gold processing industry	0.06	0.06	0.11	0.09	0.13	0.15
	Petroleum fuel industry	0.01	0.01	0.01	0.03	0.05	0.04
	General manufacturing industry	0.05	0.05	0.07	0.04	0.07	0.07
	Non-metal products industry	0.04	0.04	0.07	0.06	0.08	0.08
	Pharmaceutical products industry	0.01	0.615	0.697	0.01	0.02	0.03
	Railway manufacturing industry	0.03	0.02	0.03	0.03	0.02	0.03

Data source: Statistical Yearbook of Jiangsu Province and Statistical Yearbook of Anhui Province from 2015 to 2020

4. Research methods and data selection

4.1. Research methods

4.1.1. Orderliness model

(1) Entropy of sequence parameters

For a subsystem S_i with m sequence parameters, the entropy of the j-th sequence parameter is calculated as:

$$e_j = -\frac{1}{ln(n)} \sum_{i=1}^{n} f_{ij} ln(f_{ij}), i = 1, 2, L, n; j = 1, 2, L, m$$

$$where\ f_{ij} = \frac{s_{ij}}{\sum_{i=1}^{n} u_{ij}},\ if\ f_{ij} = 0,\ f_{ij} ln(f_{ij}) = 0$$

(2) Entropy weight of sequence parameters

The entropy weight of the j-th sequence parameter in a subsystem S_i with m sequence parameters is calculated as:

$$w_j=\frac{1\text{-}e_j}{\sum_{j=1}^{m}(1\text{-}e_j)},j=1,2,\bullet\bullet\bullet,m$$

$$where\ 0\leq w_j\leq 1,\sum_{j=1}^{n}w_j=1$$

(3) Orderliness of a subsystem

The orderliness of a subsystem S_i is calculated as:

$$x_i(s_i)=\sum_{j=1}^{m}w_j(s_{ij}),i=1,2,l,n;j=1,2,l,m$$

4.1.2. Coupling coordination model

Coupling, originally a concept in physics, refers to the phenomenon in which two or more systems or forms of motion influence each other through various interactions. The coupling degree model for multiple interacting systems can be expressed as [1]:

$$C_n=\left\{\frac{(S_1\bullet S_2\bullet\bullet\bullet\bullet\bullet\bullet S_n}{\prod(S_1+S_2)}\right\}^{1/n}$$

where Cn is the coupling degree of an n-element system, and $S_1 \ldots S_n$ represent the contributions of the first to the n-th subsystems to the overall system orderliness. The contribution of each subsystem is calculated as follows:

$$s_i=\sum_{i=1}^{m}w_{ij}s_{ij}$$

$$\sum_{j=1}^{m}w_{ij}=1$$

where s_i is the contribution of the i-th subsystem to the overall system orderliness, s_{ij} is the normalized value of the j-th indicator in the i-th subsystem, and w_{ij} is the weight of the j-th indicator in the i-th subsystem, calculated using the entropy weight method.

When calculating the entropy weights for each subsystem, normalization must first be performed. In this study, the min-max normalization method is employed: for an indicator u_{ij} where higher values are better for the system, a positive normalization is applied; conversely, for indicators where lower values are preferable, a negative normalization is used.

$$s_{ij}=\frac{x_{ij}\text{-}x_{min}}{x_{max}\text{-}x_{min}}$$

$$s_{ij}=\frac{x_{max}\text{-}x_{ij}}{x_{max}\text{-}x_{min}}$$

However, in some cases, the coupling degree alone may not adequately reflect the overall “effectiveness” and “synergy” of subsystems. The upper and lower bounds of the coupling degree for each subsystem are determined by the extreme values of the indicators, which are inherently dynamic and imbalanced. Relying solely on the coupling degree may therefore be misleading. To address this limitation, the concept of coupling coordination degree is introduced, providing a more accurate reflection of the coordinated development between enterprise scale and economic performance across 11 manufacturing industries in the eight cities of the Nanjing Metropolitan Area. The coupling coordination degree is calculated as follows:

$$C=2\left\{\frac{(s_1\bullet s_2)}{(s_1+s_2)^2}\right\}^{1/2}$$

$$D=(C\bullet T)^{1/2}$$

$$T=\alpha u_1+\beta u_2$$

where C denotes the coupling degree, D the coupling coordination degree, and T the comprehensive coordination index. The parameters α and β satisfy $\alpha+\beta=1$. Given that enterprise scale and economic performance are considered equally important in China, α and β are both set to 0.5. $D\in[0,1]$, the closer D is to 1, the better the coordination between the two systems. Conversely, the closer D is to 0, the poorer the coordination.

4.2. Discrimination criteria and grading

4.2.1. Criteria for identifying advantageous industries

Based on the properties of the location quotient, industries are classified into advantageous and non-advantageous categories. The identification criteria are shown in Table 2.

Table 2. Nanjing Metropolitan Area advantageous industry criteria

	advantageous	non-advantageous
Location entropy LQ_i	$LQ_i\geq1.0$	$LQ_i<1$

4.2.2. Criteria for orderliness

Table 3. Order degree evaluation model framework

serial number	Order degree level	the ordering index
1	the low ordering level	$[0,\frac{1}{3}]$
2	the medium ordering level	$[\frac{1}{3},\frac{2}{3}]$
3	the high ordering level	$[\frac{2}{3},1]$

As shown in Table 3, when the order degree index $S_i>[0,\frac{1}{3}]$, it corresponds to the innermost ring of the model's equipotential diagram, indicating a low level of order. When $S_i>[\frac{1}{3},\frac{2}{3}]$ 1, it corresponds to the middle ring, representing a medium level of order. When $S_i>[\frac{2}{3},1]$, it corresponds to the outermost ring, indicating a high level of order.

4.2.3. Classification and criteria for coupling degree

From the properties of the coupling formula, the coupling degree C ranges from 0 to 1, with larger values indicating stronger interconnections among subsystems. Based on coupling theory and the range of C, the interval from 0 to 1.0 can be divided into six types of coupling degrees. The specific types are listed in Table 4.

Table 4. Manufacturing coupling degree C value grade classification standard

C=0	0≤C≤0.3	0.3≤C≤0.5	0.5≤C≤0.8	0.8≤C≤1.0	C=1.0
Irrelevant state	Low-level coupling period	Antagonistic period	Breaking-in period	High-level coupling	Benign resonance coupling

4.2.4. Classification and criteria for coupling coordination degree

According to Equation (2), the coupling coordination degree D satisfies 0≤D≤1, with larger values indicating better system coordination. As illustrated in Figure 5, based on a review of relevant literature, the coupling coordination degree is divided into 10 levels using intervals of 0.1, ranging from “extremely disordered” to “excellent coordination.”

Table 5. The standard for classification of the D-value of coupling coordination degree in the manufacturing industry

Coupling coordination degree D value interval	Coordination level	Degree of coupling coordination
(0.0~0.1)	1	extreme disorder
[0.1~0.2)	2	Severe disorder
[0.2~0.3)	3	Moderate disorder
[0.3~0.4)	4	Mild disorder
[0.4~0.5)	5	Borderline disorder
[0.5~0.6)	6	Forced coordination
[0.6~0.7)	7	Primary coordination
[0.7~0.8)	8	Intermediate coordination
[0.8~0.9)	9	Good coordination
[0.9~1.0)	10	Quality coordination

4.3. Data and indicator description

4.3.1. Data description

This study evaluates the subsystem indicators of the Nanjing Metropolitan Area (NMA) based on data from the eight cities within the NMA for the period 2015–2020. The data were obtained from the Jiangsu Statistical Yearbook, Anhui Statistical Yearbook, other regional statistical yearbooks, and statistical bulletins. Indicators were selected to be either directly or indirectly calculable, and missing data were addressed using interpolation methods when necessary [4].

4.3.2. Indicator system description

To analyze the development of manufacturing in the NMA at different hierarchical levels, distinct indicator systems were constructed to meet the requirements of each level. Through frequency analysis and expert consultation, the most representative indicators were selected, covering two main dimensions: industrial scale and industrial performance. These indicators were then used to establish the orderliness model and coupling coordination model, allowing for a comprehensive analysis of manufacturing development in the NMA.

(1) Intra-regional Coupling Coordination Analysis: This focuses on the manufacturing industries within each region. For industrial scale, three indicators were selected: the number of enterprises, the number of loss-making enterprises, and the average number of employees per enterprise. For industrial performance, five indicators were selected: total assets, liabilities, main business revenue, taxes and surcharges, and total profit after offsetting gains and losses.

(2) Inter-regional Orderliness Analysis: This evaluates the development potential of manufacturing across regions. The indicators for industrial scale and industrial performance are the same as those used in the intra-regional analysis.

Table 6. Nanjing Metropolitan Area manufacturing industry evaluation system

	First Index	Second index	symbol	unit	character	Information entropy e	information utility d	wweight coefficient w
Manufacturing system	Industry size X	the number of enterprise units X1	X1	Pcs	Positive	0.940	0.060	5.423%
		the number of loss-making enterprises X2	X2	Pcs	negative	0.998	0.002	0.197%
		the average number of employees X3	X3	10,000 people	Positive	0.916	0.084	7.527%
	Industrial benefits Y	total assets Y1	Y1	100 million yuan	Positive	0.544	0.456	41.094%
		Liabilities Y2	Y2	100 million yuan	negative	0.999	0.001	0.082%
		income from main business operations Y3	Y3	100 million yuan	Positive	0.554	0.446	40.187%
		taxes and surcharges Y4	Y4	10,000 yuan	Positive	0.999	0.001	0.058%
		total profit after offsetting profits and losses Y5	Y5	10,000 yuan	Positive	0.940	0.060	5.433%

5. Collaborative analysis of manufacturing in the Nanjing Metropolitan Area

5.1. Orderliness analysis

According to the results in Table 7, the orderliness of manufacturing in the Nanjing Metropolitan Area (NMA) can be analyzed from two perspectives. From the perspective of industrial scale, during 2015–2016, the orderliness in Chuzhou, Xuancheng, Wuhu, and Huai'an showed an upward trend, with Xuancheng exhibiting the largest increase, followed by Chuzhou, Wuhu, and Huai'an. This indicates that the manufacturing development in these cities was relatively strong during this period. In contrast, the orderliness in Yangzhou, Zhenjiang, Ma'anshan, and Nanjing showed an overall declining trend, with Ma'anshan experiencing the most significant decline. From 2016 to 2020, the orderliness in Zhenjiang, Wuhu, Huai'an, and Ma'anshan continued to decrease, primarily due to an increase in the number of loss-making enterprises and a decrease in the average number of employees. Yangzhou's orderliness declined continuously from 2018 to 2020, mainly because the development potential of its pharmaceutical, railway, computer, ferrous metal, and electrical equipment industries was lower than that of other advantageous industries, resulting in uneven development of manufacturing. However, Chuzhou and Xuancheng maintained a relatively stable upward trend in orderliness, indicating that the development of industries such as pharmaceuticals and petroleum processing in these cities was gradually narrowing the gap with other advantageous industries. The orderliness in Nanjing fluctuated considerably; during 2016–2020, it experienced a pattern of decline–increase–decline–increase, primarily due to the unstable development of general equipment manufacturing, computer manufacturing, and chemical manufacturing industries. Comparing the increase in industrial scale orderliness from 2015 to 2020, the top three regions were Chuzhou, Xuancheng, and Nanjing. This indicates that the rapid growth in the industrial scale subsystem orderliness in these three cities contributed more significantly to the overall improvement of industrial scale orderliness in the NMA. The main reason is the continuous increase in the average number of employees in manufacturing enterprises in Chuzhou, Xuancheng, and Nanjing, which in turn promoted the improvement of the industrial scale subsystem orderliness in the NMA. From the perspective of industrial performance, during 2015–2017, the orderliness of the NMA first declined and then increased. However, in 2017–2018, the orderliness in Ma'anshan, Nanjing, and Zhenjiang showed a declining trend again. During 2018–2019, the orderliness rebounded, with Zhenjiang showing the most significant increase. In 2019–2020, only Chuzhou and Xuancheng exhibited an increasing trend in orderliness. Overall, from the perspective of industrial performance, the orderliness trend of the NMA's manufacturing sector was unstable, primarily because the total assets and main business revenue of the manufacturing sector accounted for a large proportion and fluctuated significantly.

Table 7. Order degree of the manufacturing industry in the Nanjing Metropolitan Area from 2015 to 2020

City	2015		2016		2017		2018		2019		2020	
	X	Y	X	Y	X	Y	X	Y	X	Y	X	Y
Chuzhou	0.0008	0.8621	0.0363	0.0008	0.0365	0.1858	0.0477	0.5074	0.0731	0.4818	0.1295	0.5166
Nanjing	0.0917	0.8325	0.0737	0.2658	0.0320	0.5613	0.0545	0.2489	0.0218	0.7438	0.0563	0.2622
Huaian	0.1186	0.7985	0.1303	0.4388	0.1300	0.6584	0.0767	0.8667	0.0392	0.7233	0.0000	0.2770
Wuhu	0.1157	0.8215	0.1299	0.3049	0.0923	0.4497	0.0756	0.5266	0.0534	0.3021	0.0009	0.1337
Xuancheng	0.0019	0.7935	0.0406	0.0438	0.0369	0.3064	0.0285	0.2743	0.0477	0.2386	0.1295	0.5655
Yangzhou	0.0823	0.8532	0.0673	0.4513	0.0570	0.4618	0.1028	0.5090	0.0713	0.7626	0.0184	0.1139
Maanshan	0.1245	0.8801	0.0962	0.7963	0.0426	0.8677	0.0229	0.0911	0.0202	0.1150	0.0032	0.0752
Zhenjiang	0.1306	0.8682	0.1189	0.0777	0.0507	0.0875	0.0306	0.0524	0.0120	0.8678	0.0009	0.4158

5.2. Coupling coordination degree

According to Table 8, in 2015, except for Chuzhou and Xuancheng, the coupling degree of manufacturing industries in the other regions of the Nanjing Metropolitan Area (NMA) remained largely stable within the range [0.800, 1.000], with coupling coordination degrees stable in the [0.9, 1.0] range. This indicates a high-level coupling state and an excellent coordination stage. For Chuzhou and Xuancheng, their coupling degree increased from a low-level coupling to a high-level coupling during 2015–2018, then declined into the antagonistic phase, whereas their coupling coordination degree continuously increased from 2016, reaching the excellent coordination stage in 2018. During 2018–2020, Chuzhou continued to rise into the adaptation phase, while Xuancheng remained relatively stable in the adaptation phase. However, the coupling coordination degree of both cities remained on average at the excellent coordination stage. From 2015 to 2020, Zhenjiang and Nanjing experienced fluctuations in the coupling process, descending from the beneficial resonance phase into the antagonistic phase, followed by rises and falls. Ultimately, Zhenjiang reached the adaptation phase, while Nanjing remained at a low-level coupling stage. Notably, Nanjing's final coupling coordination degree was higher than that of Zhenjiang. Huai'an and Wuhu exhibited consistent coupling trends from 2015 to 2020, with their coupling coordination degree trends almost identical. Their average coordination level exceeded 7, primarily because the comprehensive development level of industries such as general equipment manufacturing and chemical manufacturing in both cities was relatively strong. Ma'anshan, during 2016–2019, experienced a continuous decline in coupling degree, but its coupling coordination degree remained mostly at the medium coordination level or above. In contrast, Yangzhou's coupling degree showed a relatively stable trend compared with other cities, reaching a maximum of 0.854 in 2020, which corresponds to a high-level coupling state, while its coupling coordination degree was also at the excellent coordination stage. Based on the changes in the manufacturing coupling coordination degree of the eight NMA regions from 2015 to 2020, the development pattern of coupling coordination among cities can be ranked as: Huai'an > Wuhu > Ma'anshan > Yangzhou > Xuancheng > Chuzhou > Zhenjiang > Nanjing. This indicates that Nanjing's role in radiating surrounding cities at the manufacturing level is not prominent, whereas Anhui cities such as Wuhu, Ma'anshan, Chuzhou, and Xuancheng exhibit relatively high coupling coordination levels among different manufacturing industries.

Table 8. The coupling-coupling coordination value of the Nanjing Metropolitan Area from 2015 to 2020

Table The coupling-coupling coordination value of the Nanjing metropolitan area from 2015 to 2020

	2015			2016			2017			2018			2019			2020		
City	C	D	Coupling coordination degree	C	D	Coupling coordination degree	C	D	Coupling coordination degree	C	D	Coupling coordination degree	C	D	Coupling coordination degree	C	D	Coupling coordination degree
Chuzhou	0.199	0.315	Mild disorder	0.365	0.230	Moderate disorder	0.992	0.498	Borderline disorder	0.498	0.974	Quality coordination	0.680	1.000	Quality coordination	0.746	0.968	Quality coordination
Nanjing	1.000	0.995	Quality coordination	0.425	0.405	Borderline disorder	0.844	0.526	Forced coordination	0.526	0.286	Moderate disorder	0.262	0.222	Moderate disorder	0.298	0.472	Borderline disorder
Huaian	0.999	0.972	Quality coordination	0.827	0.724	Intermediate coordination	0.977	0.892	Good coordination	0.892	0.967	Quality coordination	0.873	0.907	Quality coordination	0.692	1.000	Quality coordination
Wuhu	0.998	0.967	Quality coordination	0.791	0.697	Primary coordination	0.971	0.742	Intermediate coordination	0.742	0.999	Quality coordination	0.745	0.963	Quality coordination	0.556	1.000	Quality coordination
Xuancheng	0.199	0.312	Mild disorder	0.349	0.235	Moderate disorder	0.997	0.548	Forced coordination	0.548	0.990	Quality coordination	0.497	0.980	Quality coordination	0.544	0.975	Quality coordination
Yangzhou	0.991	0.929	Quality coordination	0.992	0.713	Intermediate coordination	1.000	0.678	Primary coordination	0.678	0.951	Quality coordination	0.848	0.988	Forced coordination	0.854	1.000	Quality coordination
Maanshan	1.000	0.995	Quality coordination	0.996	0.910	Quality coordination	0.865	0.755	Intermediate coordination	0.755	0.712	Intermediate coordination	0.266	0.904	Forced coordination	0.306	1.000	Quality coordination
Zhenjiang	1.000	0.995	Quality coordination	0.405	0.437	Borderline disorder	0.647	0.377	Mild disorder	0.377	0.396	Mild disorder	0.220	0.563	Forced coordination	0.552	0.293	Moderate disorder

6. Conclusion

This study systematically and comprehensively measured and analyzed the development levels of ten manufacturing industries in the Nanjing Metropolitan Area (NMA) from 2015 to 2020, from the perspective of the entire metropolitan area down to each prefecture-level city, using two analytical lenses: "industrial scale" and "industrial efficiency." The research employed Location Quotient (LQ), Order Degree, and Coupling Coordination Degree models. The main conclusions are as follows:

First, from the perspective of Location Quotient analysis, there is a significant overlap of high-level advantageous industries among cities within the NMA. Cities such as Nanjing, Zhenjiang, Huai'an, Wuhu, and Chuzhou, leveraging their unique resource endowments and industrial foundations, demonstrate strong comparative advantages. In the manufacturing sector, industries including general equipment manufacturing, automobile manufacturing, computer and electronic equipment manufacturing, chemical raw materials and chemical products manufacturing, and non-metallic mineral products manufacturing are identified as core advantageous industries of the NMA. The balanced distribution of these industries not only reflects industrial synergy and complementarity within the metropolitan area but also signals the optimization and upgrading of the regional industrial structure. Notably, in sub-sectors such as railway manufacturing, computer manufacturing, and non-metallic mineral products, high LQ values are observed across multiple cities, indicating the preliminary formation of industrial clusters. This phenomenon also highlights Nanjing, as the core city of the metropolitan area, in its strong leadership and radiation capacity regarding high-end production factors such as information, capital, technology, and talent. Such unique industrial cluster advantages contribute not only to enhancing the overall economic competitiveness and innovation capacity of the metropolitan area but also to providing a solid industrial foundation for the sustainable development of all cities within the region.

Second, based on the analysis of Order Degree and Coupling Coordination Degree, the evolution of the manufacturing coupling coordination degrees among the eight prefecture-level cities from 2015 to 2020 reveals a spatial pattern of: Huai'an > Wuhu > Ma'anshan > Yangzhou > Xuancheng > Chuzhou > Zhenjiang > Nanjing. This indicates that Nanjing's role in radiating and driving surrounding cities at the manufacturing level is not prominent. By examining the temporal trends in the coupling coordination degrees, the study provides insights into the synergies and orderliness of manufacturing development among cities. The results show a specific gradient in coupling coordination states: cities such as Huai'an and Wuhu have relatively high coupling coordination degrees in manufacturing, while Nanjing ranks at the lower end of this gradient. This finding suggests that, as the core city of the metropolitan area, Nanjing's influence on surrounding cities in terms of manufacturing development has not been as significant as expected. Future development of the NMA should focus more on optimizing industrial spatial layouts, strengthening industrial linkages and resource sharing between core and peripheral cities, in order to fully leverage Nanjing's radiation and leading function and to promote the coordinated development and transformation of manufacturing industries across the metropolitan area.

7. Policy recommendations

First, the Nanjing Metropolitan Area (NMA) should strengthen the competitiveness of its advantageous industries and address deficiencies in industrial foundations, thereby enhancing the resilience of the entire industrial chain and promoting the upgrading of industrial bases and modernization of industrial chains. Efforts should focus on critical areas such as core components, software, materials, processes, and technological infrastructure, by formulating and implementing industrial capacity enhancement plans aimed at constructing a high-standard industrial base system, optimizing the industrial and supply chain layout, and strengthening risk warning and emergency response mechanisms to ensure supply chain security and stability [18]. Through industry–university–research collaboration, innovation breakthroughs in core materials, components, and software should be promoted, with particular attention to improving the performance of key industrial software, advanced gas turbine technologies, and other core products. Fiscal projects should prioritize the adoption of innovative outcomes, facilitating the bidirectional transfer of military and civilian technologies. Public service platforms should be established to enhance capabilities in R&D, design, testing, and certification, while the construction of fundamental databases and process centers should be optimized to improve the technical foundation of industrial clusters.

Second, the radiation and agglomeration effects of core cities should be leveraged to cultivate and expand manufacturing clusters, forming a new regional industrial pattern characterized by distinctive features and coordinated coupling. The eight cities along the Yangtze River should establish efficient regional coordination mechanisms, including dedicated coordination institutions or committees responsible for overall planning, policy alignment, and project collaboration in manufacturing development. Regular joint meetings and information-sharing platforms should be used to enhance communication and ensure effective implementation of cooperative measures. At the industrial level, upstream–downstream coordination should be deepened to promote inter-industry complementarity and integrated development. By jointly constructing industrial parks and alliances, enterprise cooperation and exchange can be strengthened, facilitating coordinated efforts in technological innovation, product R&D, and market development. Cross-city and cross-industry mergers and reorganizations should be encouraged to optimize resource allocation and enhance overall industrial competitiveness. Infrastructure connectivity is a critical foundation for regional coordinated development; thus, the eight cities should accelerate the construction of interconnected transportation, energy, and information infrastructure to improve regional comprehensive carrying capacity. In particular, the integration of transportation infrastructure should be reinforced to establish a convenient and efficient regional transport network, reducing logistics costs and enhancing the overall operational efficiency of the regional economy. Overall, the recommendation is for the eight cities to pursue comprehensive efforts in coupling coordination development, including establishing regional coordination mechanisms, promoting industrial synergy, strengthening infrastructure interconnectivity, advancing joint ecological protection, facilitating talent and technology resource sharing, and deepening policy coordination and institutional innovation. Implementation of these measures will effectively promote high-quality manufacturing development and comprehensive regional economic prosperity.

Third, cluster-based manufacturing industries need to further deepen industrial agglomeration, adhering to the dual strategy of "bringing in" and "going out" to form a collaborative innovation ecosystem and enhance overall competitiveness. This requires increasing R&D investment, strengthening innovation-driven development, overcoming key core technologies, and promoting sustainable industrial development [11]. In terms of international industrial cooperation, focus should be given to advanced manufacturing clusters such as high-end new materials, biomedicine, novel medical devices, and high-end equipment. Through provincial and municipal coordination strategies, foreign enterprises should be actively guided to integrate and participate deeply in the construction of China's key industrial chains, thereby promoting the bidirectional flow and sharing of manufacturing knowledge, technology, culture, and experience, and accelerating industrial internationalization. Domestic enterprises should consolidate their shares in traditional markets in developed economies and actively explore diversified markets along the "Belt and Road" countries and regions. High-level overseas economic and trade cooperation zones should be established to provide a bridge for international development of manufacturing enterprises. Enterprises should be encouraged and supported to export their advantageous production capacity, capital, brand, technical standards, and advanced management experience to enhance international market share and brand influence. Furthermore, cooperation between industry organizations and overseas Chinese business associations should be strengthened, guiding the formation of cross-national industrial alliances and jointly building a comprehensive "full-cycle support" platform for NMA enterprises to "go global." This platform would integrate policy consulting, information services, financial support, and risk prevention functions to provide one-stop, fullspectrum international services, thereby further optimizing the support system for enterprises' internationalization and helping NMA manufacturing companies better integrate into global industrial and value chains.

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