Digital Ecology Assessment Index System of Small and Medium-Sized Manufacturing Industry: A Case Study Employing Entropy Weight Method

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Abstract. The China government's 14th Five-Year Plan and the 2035 Vision set forth important plans for "Accelerating digital development" and "Creating a sound digital ecology". However, little is known about how such a digital ecology is developed and how the small and medium-sized (SMs) manufacturing enterprise could assess it. From social-technology and business perspectives, this paper first explores influential factors of such a digital ecology, followed by constructing a theoretical framework of digital ecology assessment index system for SMs manufacturing industry, then developing the practical framework of primary digital ecology assessment index system. A case study is conducted to verify the index system employing the entropy weight method for weights calculation of the indicators with sources from fifteen experts' rating, and expert opinion method used to gain wights for the second-level indicator and measurement indicator indexes as well. The final digital ecology assessment index system for SMs manufacturing industry is addressed, which is added by a five-point Likert scale for the assessment scoring. Four levels of the digital ecology maturity of the SMs manufacturing industry were primarily proposed finally as a general guideline for the industry and the enterprise to create and monitor the open and safe digital ecology for their sustainable development. The digital ecology assessment index system for SMs manufacturing industry that this study has attempted to develop and four levels of digital ecology maturity proposed fill content to the current existing literature and practice as contributions by this research.

Keywords: Digital ecosystem; Digital ecology; Digital ecology assessment; Digital ecology assessment index system; Small and medium-sized manufacturing industry

1 Introduction

Technology realizes digitalization connecting everything with everything in this emerging digital world. We live under the what called the techno-ecological condition of our time (Hörl, 2017b) [1]. IS research is engaging with this techno-ecological condition under the label of digital ecosystems (Marton, 2022)[2], in which the term of ecosystem refers to a collection of actors and artefacts that organize and coalesce around an integrating organization and/or platform. The notion of ecosystem was first introduced into the social economy academic research in 1993 by American economist Moore, to refer to the interaction between organizations and the environment (Wang et al., 2022)[3], in order to better capture the kind of

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innovation and value creation increasingly occurring across conventional boundaries of formal organizations, industries, sectors, and markets (Moore 1993)[4]. Jiang (1999)[5] proposed the logical concept of "digital ecology" with which ecological integration of the social system can be realized through the internet.

Focusing on SMs manufacturing industry, this paper attempts to explore the concept of digital ecology and its influential factors, followed by construction of theoretical framework of digital ecology assessment index system for SMS manufacturing industry, which serves for the enterprise and the industry as guidelines to diagnose and monitor their digitalization development.

2 Literature Review

Digital ecosystem, from an ecology perspective, is defined as "a digital environment populated by digital species or digital components which can be software components, applications, services, knowledge, business processes and models, training modules, contractual frameworks, law, etc."(Fu, 2006)[6], in which a digital component can be any useful idea, expressed by a language (formal or natural), digitalized and transported within the ecosystem, and which can be processed by humans or by computers (Fu, 2006[6]). Xia (2021)[7] considers that digital ecology is an approach involving stakeholders such as the government, enterprises and consumers, taking digital infrastructure and industrial internet platforms as the starting point, and taking material, information, data and other all-factor resources as the carrier. Wang (2021)[8] identified six types of ecosystems related to innovation at different levels, such as product and/or service ecosystem at product/service level. The product ecosystem includes the providers of a focal product, and the complementary products and services needed to create a whole solution for the customers to buy, while service ecosystem is self- contained adaptive system of actors interacting to exchange service by integrating their or others' resources. This study takes a lens of product ecosystem to explore the the theoretical framework and the assessment index system of SMs manufacturing digitalization ecology.

Briscoe (2010)[9], taking a social-technology perspective, proposed the concept of an applied digital ecosystem (Figure 1) which is combined a digital ecosystem and a social ecosystem, stating that therefore, any distributed adaptive open socio-technical system, inspired by biological ecosystems, possesses three properties of self-organisation, scalability and sustainability. Moreover, a digital ecosystem is a dynamic, complex system of systems that possesses all the characteristics of these systems, such as dynamic, high-dimensional and non-linear. According to Briscoe (2010), digital ecology is one of components of an applied digital ecosystem. The concept of digital ecology has been applied to many fields such as urban construction, urban and rural planning, rural revitalization, and corporate ethics and responsibility (e.g. Cao and Li, 2012[10]; Tao, 2013[11]; Ye, 2021[12]). Luo (2022)[13] studied on symbiosis mechanism of manufacturing digital innovation ecosystem, considering that manufacturing digital innovation ecosystem is a dynamic system composed of manufacturing enterprises, consumers, digital platforms, research institutions and other stakeholders (e.g., government, suppliers, intermediaries), which integrates a value proposition, using digital technology and digital data to promote the innovation of products, services, business processes or business models in order to achieve value creation. Dong et al. (2007)[14] defined the digital ecosystem as a distributed, adaptive and open socio-technological system, with self-organization, scalability and sustainability.

3 Factors Influencing Small and Medium-Sized Manufacturing Digitalization Ecology System

Based on Nick et al.'s CCMS Model theory (2020)[15] and Schumacher & Sihn (2018)[16], from social-technology (Briscoe, 2010)[9] and business perspectives, this study considers that the SMs manufacturing digitization ecology rests on seven influential factors as follow, including: (1) Information, data and platform: Technical communication Infrastructure; Utilization of collected data; IT development and vertical integration; (2) Applied intelligent technology: Automatic, adaptive control of production; Intelligent technologies to be applied; (3) Digitalizaiton human resource: Workforce availability; Openness to new technologies; Education and training; (4) Customers and market demand; (5) Business funding and company digital management: Business funding; Digital-knowledge; Ability in data secure guarantee, and Recruitment strategy; (6) Value creation via smart product and service; (7) Suppliers and value chain.

4 Building Digital Ecological Evaluation Index System of Sms Manufacturing Industry

According to the logic of index building, i.e. "Input→Transformation→Output" (Wang et al., 2022)[3], this study proposes the digital ecological assessment index system which is composed of three dimensions (Figure 1), namely: input (digitalization foundation and digital infrastructure), transformation (digital capacity), output (organization performance). The dimension of Input mainly refers to digitalization foundation and digital infrastructure, whilst the Transformation refers to digital capability to transform input factors into application outputs, and Output refers to organization performance from a business perspective. Under each dimension, there are several secondary indexes (influential factors, see Figure1). The theoretical framework of digital ecology assessment index system for SMs manufacturing industry is addressed as shown in Figure 1, which is composed three first-level indicators and eight second-level indicators.

4.1 Dimension of digital foundation and infrastructure

The dimension of digital foundation and infrastructure reflects the input of elements in the development of digital ecology, including infrastructure, data resources and digital platforms, intelligent technology for production and logistics. First, Information infrastructure can enhance data perception, transmission, storage and computing capabilities, including 5G, Internet of Things, industrial Internet and other communication network infrastructure, artificial intelligence, cloud computing, blockchain and other new technology infrastructure, as well as data centers, super-computing centers and other computing infrastructure. With support by information infrastructure, intelligent technology can be applied into practice. The importance of digital technologies lies in its providing the information needed to support the interactions and tasks for innovation in ecosystems of varying scales (Wang, 2021: 397-422)[8].

Second, it is considered that customer resource and market demand are the important foundation of the development of digital ecology. Digital customer orientation, as a new capability, helps manufacturing SMEs to create value, which is defined as offering customized and enriched customer experiences made possible by embracing digital ecosystems (Kopalle et al., 2020)[17].

4.2 Dimension of digital capacity

The dimension of digital capability reflects the quality and efficiency of digital ecology to transform input factors into application outputs (Wang et al., 2022)[3], including digital talents and resource, company digital management&operating, and digital supplier&value chain. First, digital talent (human resource) is the first productive force for turning out the value of data into creating value for customers, which is related to high knowledge density of data. With talents in areas such as digital strategy management, in-depth analysis, product development, advanced manufacturing, digital operations, the value of data is possible be discovered, exploited, and realized. Second, the company's digital capacity also reflects the company digital management on funding and digital security (Wang et al., 2022)[3] and on utilization of digital supplier&value chain.

4.3 Dimension of organization performance

Ecosystems form to create value for their customers and, ultimately, to make a profit as a value network, which are defined and studied as business and innovation constellations (Alaimo, et al., 2019[18]; Constantinides, et al., 2018[19]; Phillips and Ritala, 2019[20]). The digital ecology enhances manufacturing SMEs to create the customers value through smart products and services, in turn, it enhances the corporate sustainable development of the enterprise and the industry. Modern production is a continuous process of transformation towards economic, ecological, and social sustainability (Schöppenthau, et al., 2023) [21]which is supported by various activities in ministries, as well as in China.

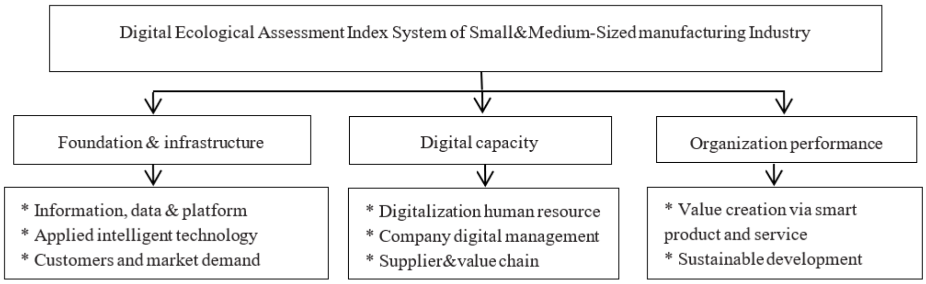

Figure 1. Theoretical Framework of Digital Ecology Assessment Index System for SMs Manufacturing Industry

4.4 Practical framework of digital ecology assessment index system

Based on the aforementioned analysis and the proposed theoretical framework, and based on Schumacher et al.(2018)[16] and Yu,et al.(2022)[22], the practical framework of primary digital ecology assessment index system is firstly developed (Table 1), which is composed of five aspects, including first-level indicators (dimension), second-level indicators, measurement indicators, weights and source of indicators. The digital ecology assessment index is an overall index built on the basis of sub-indexes.

For this study, we invited four experts to participate in this research as the source of indexes of first-lever indicators by asking them to rate the weights for the indicators, among those three are local college professors specializing in digitalization of manufacturing industry and one is general manager of the case enterprise of this study. The entropy weight method was mainly used to calculate the wights. The index calculation and methods used are detailed as below.

The measurement indicators are standardized. Missing values are supplemented by regression based on relevant economic statistics. The scores of measurement indicators and second-level indicators are determined by entropy method, and the weights of first-level indicators are based on the opinions of experts. Second, the total digital ecological index and the first-level index are calculated by means of geometric weighted average, which reflects the balanced development of sub-indicators. The secondary indexes are calculated by means of arithmetic weighted average, which shows that the sub-indexes are fungible to each other. Based to Wang et al. (2022), the specific calculation steps are as follows:

(1) Standardization. Data is standardized using Min-Max method:

$$\mathrm{Z} = \frac{X - \min X}{\max X - \min X} \times 90 + 10$$

(2) Entropy weight method. The entropy method is used to determine the weight of the secondary index and the measurement index. The greater the dispersion degree of the index, the smaller the entropy and the greater the weight. Indicators are processed as follows:

$$p_{ij} = x_{ij} \div \sum_{i=1}^{n} xij$$

Where *xij* is the level of case *i* on indicator *j*, which is the result of the original value of indicator after standardization. P_{ij} is the result of standardizing them, and we can then treat it as a discrete distribution on the interval [0,1], using this to calculate the information entropy of the index. In information theory, if the distribution of a random variable is concentrated, the uncertainty is smaller, the entropy is smaller; Conversely, if the distribution of random variables is more dispersed, the uncertainty is larger, and the entropy is larger. According to the entropy, the degree of dispersion of index *j* is calculated:

$$ej = -\frac{1}{1nn} \sum_{i=1}^{n} p_{ij} 1np_{ij}$$

Then, combined with the results of entropy and dispersion degree, the weights of indicators are calculated:

$$W_j = \frac{1-e_j}{\sum_{j=1}^{m} 1-e_j}$$

(3) Sub-index polymerization method. The first-level indicator index is calculated by geometric average as follows:

$$Y = \prod_{k=1}^{K} X_k^{W_j}$$

(4) The total index is aggregated according to the corrected weights. The entropy weight method assigns more weight to indicators with large data differences. In fact, the index with good and stable data source (e.g. the measurement index data under the second-level index) generally have less weight, while the index with more missing values gains the most weight, which cannot objectively reflect the development distribution of digital ecology. To this end, in the synthesis of first-level indicators, the arithmetic average is calculated using the weight after discussion and correction by experts. In particular, for the first-level indicators, the indexes of digital Foundation & infrastructure, Digital capacity, and Organization performance are 0.24, 0.4 and 0.36 respectively. This result is similar to the research result of Wang et al. (2022) but who studied on the digital ecology of China cities (the indexes of the digital basis, the digital capability, and the digital application are 0.3, 0.3 and 0.4 respectively).

Table 1. Practical Framework of Primary Digital Ecology Assessment Index System.

First-level indicator	Second-level indicator	Measurement indicator (MI)	Weight calculated with source from Exp-Op			MI Adapted from
Digital Foundation & infrastructure	Information, data & platform	Digital infrastructure	0.24	6%	2%	China National Engineering Lab
		Data flow level			2%	Tsinghua University Internet Industry Research Institute
		Digital platform			2%	Nick et al.(2019)
	Applied intelligent technology	Advanced technology being applied		6%	2%	Schumacher et al.(2018); Yu,et al.(2022)
		Ability in applying technology to practice			4%	Schumacher et al.(2018); Yu,et al.(2022)
	Customers and market demand	Purchasing power of customers		12%	5%	Schumacher et al.(2018); Yu,et al.(2022)
		Market demand			4%	Expert interview
		Market size			3%	Expert interview
Digital capacity	Digitalization human resource	Digital knowledge intensive employees	0.4	16%	8%	Shanghai Academy of Social Sciences
		Employee digital literacy			4%	Schumacher et al.(2018); Yu,et al.(2022)
		Digital talent recruitment and training			4%	Schumacher et al.(2018); Yu,et al.(2022)
	Company digital management	Managing on funding & budget		15%	5%	Expert interview
		Efficiency of digital management			10 %	Schumacher et al.(2018); Yu,et al.(2022)
	Supplier& value chain	Digital decision-making in supplier selection		9%	5%	Schumacher et al.(2018); Yu,et al.(2022)
		Completeness of digital value chain			4%	Expert interview

Organization performance	Value creation via smart product and/or service	Customer satisfaction with product and/or service		18%	9%	Expert interview
		Smart product/ service competitiveness			9%	Expert interview
	Sustainable development	Competitiveness of the organization	0.36	18%	9%	Moldavska and Welo, 2019
		Reliability of the product			9%	Moldavska and Welo, 2019

Note: SMs = small and medium-sized; Exp-Op=expert opinion

In order to verify the practical framework of primary digital ecology assessment index system, we conducted a case study by inviting three out of fifteen experts mentioned above to in-site assess a legacy medium-sized

manufacturing enterprise (namely: AHY) in a strong-manufacturing-industries city (Dong-guan city) in Guangdong province, South China, which has specialized in computerized embroidery for fifteen years with it self-owned factory, with less than 70 employees and yearly operating income of about 40,000 million yuan.

Moreover, the five-point Likert method is employed to score each measurement index, adding to the practical framework of primary digital ecology assessment index system (Table 2) , with 1 as lowest score (equal to 20 scores in centesimal system), 5 as highest score. The three experts were asked to give a scale (1 to 5) for each measurement indicator. The final digital ecology assessment of SMs manufacturing industry was addressed after the case study and the examination by the three experts, which is composed of nineteen measure indicators are developed under the eight second-level indicators.

According to Digital Transformation Development Report for small and medium-size enterprise (2023) released by China Industrial Internet Research Institute, we proposed the four levels of the maturity of digital ecology of the enterprise based on the total assessment scores. (1) Level one (<40 scores) : is the initial start-up period, when the enterprise is in the ignorant initial stage of digitization, and only has carried out simple information technology application within a single functional scope to realize basic data process sorting and standardized data management, but it has not effectively played the role of information technology in supporting its main business. (2) Level two (40 to 60 scores) : is the single point trial period, when the enterprise is in the research and exploration stage of digital transformation, and only tried digital applications in a single field, such as establishing e-commerce capabilities, placing digital advertisements, etc., and starts process standardization and informatisation in some core businesses. At this phase, IT mainly assumes the role of support services, mainly to improve process efficiency, limited cloud, yet has not yet formed a data center. (3) Level three (61-79 scores) is the called comprehensive construction period, when after a single point attempt and continuous positive feedback, the enterprise carried out local digital construction with points and areas with its own data center, to develop its own digital strategy and management for value creation. The digital value begins to emerge with each line of business accumulating a certain amount of data. (4) Level four (≥80 scores) is the period of digital intelligence innovation, when the enterprise has basically completed digital transformation, owning a company-level digital base and a corporate digital business center. AI technology is widely applied into production and logistics, helping the enterprise keep on creating competitive and reliable quality product and/or service to the customer and the market, whilst the data-driven intelligent operation of the whole value chain has been realized.

Table 2. Case Study of Digital Ecology Assessment on the SMs Manufacturing Enterprise of AHY

First-level indicator	Second-level indicator	Measurement indicator	Indicator weight		5-point scale	Cente-simal score	Sum
Digital foundation & infrastructure	Information, data & platform	Digital infrastructure	6%	2%	4	80	1.6
		Data flow level		2%	4	80	1.6
		Digital platform		2%	4	80	1.6
	Applied intelligent technology	Advanced technology being applied	6%	2%	4	80	1.6
		Ability in applying technology to practice		4%	3	60	2.4
	Customers and market demand	Purchasing power of customers	12%	5%	5	100	5
		Market demand		4%	3	60	2.4
		Market size		3%	3	60	1.8
Digital capacity	Digitalization human resource	Digital knowledge intensive employees	16%	8%	2	40	3.2
		Employee digital literacy		4%	2	40	1.6
		Digital talent recruitment and training		4%	2	40	1.6
	Company digital management	Managing on funding & budget	15%	5%	3	60	3
		Efficiency of digital management		10%	3	60	6
	Supplier& value chain	Digital decision-making in supplier selection	9%	5%	2	40	2
		Completeness of digital value chain		4%	5	100	4
Organization performance	Value creation via smart product and/or service	Customer satisfaction with product and/or service	18%	9%	4	80	7.2
		Smart product/ service competitiveness		9%	4	80	7.2
	Sustainable development	Competitiveness of the organization	18%	9%	3	60	5.4
		Reliability of the product		9%	4	80	7.2
Total score							66.4
Level of digital ecology maturity		L1(<40) ☐	L2 (40-60) ☑		L3(61-79) ☐		L4(≥80) ☐

From Table 2, it is seen that the total assessment score is 66.4, meaning the level of digital ecology maturity of the case enterprise is L2 (40 to 60 scores), that is the enterprise is in the single point trial period towards digitalization.

5. Conclusion

To build up a safe, open and healthy digital ecology for SMs manufacturing industry is strategically forward-looking for the industry long-term sustainable development. The digital ecology in SMs manufacturing sector is backed by by its mysterious digital rule system. As there is little related literature, this paper, from social-technology and business perspectives, explores the influential factors of digital ecology of small and medium-sized manufacturing industry. The paper constructed the theoretical framework of digital ecology assessment index system, which is composed of three first-level indicators, eight second-level indicators, and nineteen measure indicators under the second-level indicators, and then developed the practical framework of primary digital ecology assessment index system, in which the entropy weight method was employed to calculate the weights of indicators with sources from fifteen experts' rating. A case study was conducted to assess the digital ecology of a SMs manufacturing enterprise in Dong-guan city of Guangdong province, China with the participation of three experts. The five-point Likert scale was added to the practical framework of primary digital ecology assessment index system for assessment scoring. Moreover, four levels (Level one to four) of the digital ecology maturity of the SMs manufacturing industry were proposed as general guideline for the industry and the enterprises to monitor and to create the open, healthy and safe digital ecology. Theoretical and practical framework of digital ecology assessment index system for SMs manufacturing industry proposed fill in content the current literature, which serves as an introduction for related further research. Future research need to conduct survey to obtain various data sources, with a sample of different kinds of manufacturing SMEs and a combination of the entity and organizations (e.g. academics institutions, industry associations, government).

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