Monitoring Index System for Sectors’ Digital Transformation and Its Application in China

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Abstract: Presently, for the purpose of sustainable growth of the economy, it is a common choice to promote sectors’ digital transformation (DT). However, to credibly monitor the effect of DT on sectoral development, it is necessary to develop a systematic measure for the monitoring sector’s DT. This study provides a monitoring index system for sectors’ DT. First, an assessment framework for enterprises’ DT is introduced, which laid a foundation for the proposed monitoring index system for sectors’ DT. Secondly, a monitoring index system for sectors’ DT is established, which includes 13 monitoring indexes from four aspects, namely transformation stages, single-domain digitalization, integration and interconnection, and collaboration, interaction and mode innovation. A weighted method of interval hesitant fuzzy entropy is also given here. Finally, a panorama of sectors’ DT in China is derived by applying the proposed monitoring index system, and a prediction that the level of sectors’ DT in China will continue to grow in the next three years is made by gray predication.

Keywords: sectors’ digital transformation; monitoring index system; assessment framework; interval hesitant fuzzy entropy; gray predication

1. Introduction

Over the past decade, big data, the Internet of Things, artificial intelligence, and other information and communication technologies (ICTs) have developed rapidly and penetrated into traditional industries quickly, causing a systematic and holistic industry innovation and technology revolution. Being data-driven is the key characteristic. Moreover, the economic development mode is transforming from material-dominated production to information-dominated production. Digital transformation (DT) has become the focus of all enterprises. Enterprises in China use DT to enhance corporate competitiveness and seek a comprehensive DT during these years. According to a survey, DT has been adopted as the core strategy in over 70% of China’s top 1000 enterprises in 2018, and 65% of China’s GDP will be related to data resource by 2022 [1]. In the context of the industrial revolution, sectors’ DT has been recognized worldwide as a necessary way to achieve economic innovation and development [2].

The core of DT is the application of ICTs, and the overall digitalization and cross-links of the value creation processes. From the perspective of enterprises, these changes brought by a successful DT can be realized only if it is implemented in their strategy level [3,4]. DT implies new ways of combining various products and services [5], and stimulates the emergency of new business modes such as digital platforms [6]. Enterprises expect major long-term gains in efficiency and productivity by applying DT [7]. Kohli et al. [8] examined seven dimensions of an adapted theoretical framework, including initiation, development, implementation, exploitation, the role of the external competitive environment, the role of internal organizational environment, and outcomes of product, service, and process, and suggested several areas of future research.
From the perspective of sectors, DT lies not only in the gains in efficiency and productivity, but also the degree of popularization and promotion of DT in the sector, as well as the formation of the sector ecology and the common prosperity of the sector chain. Some government departments, institutions, and scholars conducted research on the sectors’ DT. The development research center of the state council of the People’s Republic of China (PRC) [9] put forward a set of digitalized system architecture, which can cover agriculture, industry, and service sectors involving a digital layer, platform layer, and physical layer. Digital development is a strategic choice to build a new competitive advantage for the country in the digital age. They formulate national strategies, plans, and policies to support the DT and upgrading of sectors. The “OECD Digital Economy Outlook 2015” report shows that 80% of OECD member countries have formulated national strategies or departmental policies, established the system of national strategies related to DT by 2015 [10]. The White House of the United States released a digital strategy plan and deployed a series of related supporting measures to accelerate the implementation of its digital strategy [3]. The UK digital strategy issued by the government takes connectivity, skills and inclusiveness, digital sector, macro-economy, cyber space, digital governance, and data economy as main strategic tasks [11,12]. Germany initiated “Industry 4.0,” which takes “cyber-physical systems” (CPS) as the core and promotes the in-depth application of ICTs in industries to realize seamless data transmission, accurate control of equipment, and intelligent interactions among production processes [13].

However, compared to enterprises’ DT, the sectors’ DT is a more complex system in terms of engineering, which involves promotion and application of technology innovation, management optimization, organizational change, data mining, use, etc. in the entire sector. Meanwhile, in this long-term process, we should track the development of the sectors, monitor the risk of this process transformation, and ensure the effectiveness of the transformation.

How to carry out DT at the sector level is the key. Unified and systematic methods for evaluating the effects of sectors’ DT have not yet been formed. It is necessary to establish a set of universal indexes that quantify the level and effect of sectors’ DT to guide various sectors to carry out DT scientifically and effectively.

In addition to the previous research work, there are still some problems to be addressed: (1) A universal index system that quantify the level and effect of DT of various sectors is still needed to be investigated.

(2) Application of the universal index system whether objectively reflect the level and effectiveness of sectors’ DT of a country still needs to be proved by practice.

To answer these questions, we put forward a monitoring index system for sectors’ DT based on previous theoretical research and industrial practices [14]. Based on data from a large number of enterprises in China, we organized an overall statistical analysis to quantitatively monitor the development level and effects of sectors’ DT in China. With the monitoring index system the status of sectors’ DT in China was determined, characteristics of that was analyzed, and the priorities and path were clarified.

The remaining parts of this study are as follows: Section 2 is the overview of previous relevant research on DT, as well as different approaches in assessment for DT. Section 3 gives an assessment framework for enterprise’ DT. On this basis, Section 4 proposes a monitoring index system from the perspective of sectors, design a set of monitoring indexes as well as their weight and calculation methods. Section 5 shows the status and analysis of sectors’ DT in China by applying the monitoring index system. Section 6 gives a prediction of sectors’ DT in china and Section 7 provides the conclusion and future work.

2. Literature Review

In this section, we first review current studies of DT from perspectives of promotion initiatives, influencing factors, etc. Then the existing technology is sorted out and the assessment of DT is discussed.
2.1. Digital Transformation

Heated academic and industrial discussions are carried on DT \cite{4,13,15,16}. They reached a consensus that DT is not only has an effect on technology shift \cite{17–19}, but also on business modes, user experiences and operational processes \cite{20–23}. Therefore, discussions are mainly from the perspectives of emerging technology innovations, organizational management, business mode changes, etc.

In the aspect of technology innovation and adoption, experts address that in the digital age, smart products need to be created with high technologies in intertwined digital and physical processes \cite{24}. Emerging ICTs are considered to be important drivers in the process of DT, including information systems \cite{25}, big data \cite{26,27}, cloud computing \cite{28}, three-dimensional printing \cite{29,30}, and the Internet of Things \cite{31}.

In the aspect of organizational management, Sandberg et al. \cite{32} presented principles for examining digital options for a specific business process, which will help industries to realize a set of desirable and feasible IT capability investments. Li Jun et al. \cite{33} analyzed the key elements of sectors’ DT in China, especially the organizational form innovation.

From the point of view of business mode changes, researchers consider that DT introduces digital technologies which bring about innovation of business mode, then result in major changes of enterprises’ products, organizational structures and capability of process automation \cite{34,35}. In the face of rapidly changing customer needs, these changes enable companies to adjust in time and respond flexibly \cite{36}.

2.2. Assessment of Enterprises’ Digital Transformation

It is a process of long-term optimization and continuous evolution to promote DT. Despite the multiplicity of technological novelties and implementation methods, DT has taken a much longer time and faced much more difficulty than expected \cite{37,38}. It is essential to quantitatively monitor and comprehensively evaluate the level and effect of DT. Different methods are used in the evaluation of DT, mainly through the evaluation of digital maturity or that of integration of informatization and industrialization.

The concept of digital maturity was proposed mostly by scholars or industrial practitioners in traditional industrial countries. Digital maturity was designed for enterprises from all industries \cite{39} assessing their current business mode against emerging opportunities and potentially adapt it to the new digital era \cite{40}. The same for several other tantamount terms, such as digital readiness \cite{41} or DT index \cite{42}. To organize assessment based on digital maturity, RWTH Aachen University, Heinz Nixdorf Institute, DFKI, Fraunhofer Research Institution, Technische Universität Darmstadt and Acatech launched jointly the Industry 4.0 Maturity Index Report. The ability of industry 4.0 is evaluated from four aspects, i.e., resources, information system, organization management, and cultural focus on the IoT information system \cite{43,44}. Based on the maturity model, digital readiness assessment \cite{45,46}, enterprises architecture improvement \cite{47}, industrial digitalization roadmap \cite{48,49}, and smart factory implementation \cite{50} are analyzed. However, the applicability of the digital maturity assessment is limited. On the one hand, Remane et al. \cite{51} claim that digital maturity is typically described along a linear scale, thus assuming that all enterprises do and need to proceed through the same path, which seems to be a critical oversimplification that invites faulty thinking with the possibility of leading to wrong management decisions. On the other hand, from our observation in the context of industrial developing countries including China, most enterprises are now at the stage of Industrial 2.0, and a few of them are experiencing a transition from Industrial 2.0 to Industrial 3.0 \cite{52}. Therefore, for most enterprises, existing assessment models or indexes, such as maturity model and readiness indexes in the scenario of Industrial 4.0, are not suitable for them to continuously monitor all the stages of their DT development.

Another widely used method for evaluating DT is that of Integration of Informatization and Industrialization (III), which was proposed mainly by scholars in China. It aims at helping enterprises to improve their competitive advantage in the digital era through continual assessment of their capability in the context of III, which is one of the major
development path of enterprises in China in the digital era. Zhang Xin et al. [53] provided several indexes for III assessment, including III level index, informatization index, industrialization index, etc. and organized empirical research at the provincial level. Zhou Jian et al. [54] proposed a framework and method of III assessment which covered the whole lifecycle of manufacturing enterprises based on industrial practices of enterprises in China. Yu Chang-yue et al. [55] proposed an evaluation indicator system constituted by aspects of innovation driving, integrated development, scale, quality, sustainability, etc. and investigated the III development level in major provinces in China.

2.3. Monitoring of Sectors’ Digital Transformation

The successful cases of enterprises’ DT drive the development of sectors. The authors tried to monitor DT of an entire sector. However, existing assessment indicators are mostly designed from the perspective of enterprise individuals. There is a gap in the research of assessment and continuous monitoring in the sector level. Therefore, in order to provide insightful advice to policy makers, enterprises’ managers, capital investment bodies and other related stakeholders, it is of great importance to develop a universal monitoring index system for major sectors and establish a monitoring mechanism for continuous tracking of their development about DT.

In most current research on sectors’ DT, case studies are commonly used, which are carried out in micro-perspective due to the limitations of inadequate data in empirical studies, and usually draw just referential conclusions. However, in order to systematically and comprehensively study and evaluate sectors’ DT, data of up to hundreds of enterprises are essential in a statistical sense.

To fill the above-mentioned gap, we investigate current situation and further needs of vast Chinese enterprises which are incorporated into the design of monitoring index, and propose a monitoring index system for sectors’ DT. Moreover, we are engaged in promoting the index system and have attracted over 99,910 Chinese enterprises to use it online in recent years, which has achieved the coverage of entire-process, multi-angles and continuous monitoring. By analyzing the large amounts of data, the effective monitoring of sectors’ DT is fulfilled.

The major contributions of this research can be seen as follows: First, for the purpose of continuous monitoring development of sectors’ DT, this study provides a systematical and comprehensive monitoring index system and calculation methods, which could derive the panorama of a country’s DT. Second, the panorama of DT in China is presented by applying the monitoring index system, which could be a reference to other countries.

3. Introduction to the Assessment Framework for Enterprises’ Digital Transformation

DT contains three parts, i.e., idea transition, mode transformation and path innovation. The assessment framework of enterprises’ DT in [14,56] plays an active part over the past decade, which laid the theoretical foundation for the research of this article.

As shown in Figure 1, the assessment framework of enterprises’ DT is composed of two parts, i.e., progress assessment and impact assessment. In the integration process of industrialization and industrialization, enterprises are advancing step by step along four stages in both enterprise competitiveness, and economic and social benefits. The four stages are basis and support, domain application, integration and interaction, innovation, and disruption.

According to the assessment framework, a set of assessment indicators with three levels are shown in Figure 2.
Figure 1. Assessment framework of enterprises’ digital transformation.

According to the assessment framework, a set of assessment indicators with three levels are shown in Figure 2.

Figure 2. Assessment indicators of enterprises’ digital transformation.

4. The Proposed Monitoring Index System for Sectors’ Digital Transformation

4.1. Monitoring Index System for Sectors’ Digital Transformation

After the assessment framework and indicators for enterprises’ DT were put forward, a large number of Chinese enterprises took it as a judgment and reference for evaluating and guiding DT in enterprises. The successful DT of some advanced enterprises has led to the continuous advancement of the entire sector’s DT process. In this case, in order to effectively monitor the level of sectors’ DT and derive a panorama of DT at sector level, the author team proposed a monitoring index system for sectors’ DT based on the assessment framework and indicators for enterprises’ DT. Current situation and further needs of vast enterprises, such the development and application of AI, blockchain, cloud and data analytics, and big data-driven are all be taken account into the design of the monitoring index system [57,58].
The proposed monitoring index system consists of 13 monitoring indexes concerning sectors’ DT, which is distributed in four aspects, i.e., single-domain digitalization, integration and interconnection, collaboration and interaction, and mode innovation, as shown as Table 1.

### Table 1. Proposed Monitoring Index System for Sectors’ DT.

| Monitoring Priorities            | Monitoring Indexes                                                                 |
|---------------------------------|-----------------------------------------------------------------------------------|
| Single-domain digitalization    | - Digital rate of production equipment  
                                 | - Digital R&D tool application rate  
                                 | - Numerical control (NC) rate of key processes  
                                 | - E-commerce application rate |
| Integration and interconnection | - Proportion of enterprises that achieve the integration of design and manufacturing  
                                 | - Proportion of enterprises that achieve integration of supply production-sale  
                                 | - Proportion of enterprises that achieve integration of management and control |
| Collaboration and interaction   | - Proportion of enterprises that achieve the control of the whole lifecycle of products  
                                 | - Proportion of enterprises that achieve the collaboration over the industry chain  
                                 | - Smart manufacturing readiness rate |
| Mode innovation                 | - Proportion of enterprises that achieve networked collaboration  
                                 | - Proportion of enterprises that achieve service-oriented manufacturing  
                                 | - Proportion of enterprises that achieve personalized customization |

### 4.2. Index Set for Monitoring Sectors’ Digital Transformation

In this section, the indexes for monitoring sectors’ DT are designed from four aspects, i.e., single-domain digitalization, integration and interconnection, collaboration and interaction, and mode innovation.

#### 4.2.1. Indexes of Single-Domain Digitalization

The indexes of single-domain digitalization are as follows:

(a) Digital rate of production equipment, which refers to the ratio of the quantity of digitalized production equipment to the quantity of all production equipment. Specifically, in process industry, digitalized production equipment means independent equipment which can collect information automatically. In discrete industry, digitalized production equipment means NC machines, CNC machine centers, industrial robots, electromechanical equipment with data interface and so on.

(b) Digital R&D tool application rate: Digital R&D design tools mean software tools that are able to help enterprises in product design. These tools enable the enterprises to fulfill many tasks in digital form, such as modeling, simulation, verification and so on. In discrete industries, it refers to the ratio of the quantity of enterprises which can carry out 2D or 3D digital modeling to the quantity of all enterprises. In process industries, it refers to the ratio of the quantity of enterprises that use digital methods in R&D design.

(c) Numerical control (NC) rate of key processes: In discrete industries, it refers to the coverage rate of numerical control systems in key processes. NC DNC and CNC FMC are both typical numerical control systems. In process industries, it means the coverage rate of process control systems in key processes. PLC, DCS, and PCS are all typical process control systems.

(d) The E-commerce application rate refers to the fact that that the transactions of products or services are completed through the Internet. In related enterprises, the payment
and delivery of those transactions are completed “online” or “offline”. It should be noted that orders which are received or dispatched by phone, fax or E-mail are not in the scope of E-commerce.

4.2.2. Indexes of Integration and Interconnection

The indexes of integration and interconnection are as follows:

(a) Proportion of enterprises that achieve the integration of design and manufacturing: In the enterprises that achieve the integration of design and manufacturing, data from product design, process design, and product manufacturing are integrated, and the information among those are also transmitted automatically.

(b) Proportion of enterprises that achieve integration of supply production-sale: In the enterprises that achieve integration of supply production-sale, by integrating corresponding information systems, integrated operation between links on internal supply chain can be achieved, so that the management for the procurement of materials, the warehouse of primary materials and completed products, the sales of products, etc. can be seamlessly connected with financial management by collecting automatically data from the integrated information system without manual input.

(c) Proportion of enterprises that achieve integration of management and control: In the enterprises that achieve integration of management and control, corresponding information systems are integrated so that seamless connection is achieved among enterprise production management (plan layer), workshop manufacturing execution (execution layer), production and manufacturing process control (control layer). The upload of information and the send of instructions can go through the above links.

4.2.3. Indexes of Collaboration and Interaction

The indexes of collaboration and interaction are as follows:

(a) Proportion of enterprises that achieve the control of the whole lifecycle of products: In the enterprises that achieve the control of the whole lifecycle of products, all data throughout the product life cycle is managed and used effectively, including product design, technological design, production and manufacturing, field installation, and debugging. Moreover, information can be transmitted automatically not only between product design and process design but also between process design and manufacturing. In addition, unified definitions of digitalized products are applied at all stages of the whole lifecycle of products.

(b) Proportion of enterprises that achieve the collaboration over the industry chain: In the enterprises that achieve the collaboration over the industry chain, the information system is used to achieve the collaborative operation of core businesses such as R&D, procurement, production, sales, finance, etc. with their upstream and downstream enterprises in the industry chain.

(c) Readiness rate of smart manufacturing: In the enterprises that achieve smart manufacturing, the NC rate in key processes exceeds 50 percent, and the integration of supply production-sale has almost completed. These enterprises have high NC degree of underlying equipment, and achieve not only the integration of procurement, production, sales, inventory, and finance on internal supply chain but also that of management and low-level automation. These enterprises tend to be intelligent factory or intelligent enterprises, and have formed the networked, flexible, and intelligent manufacturing mode.

4.2.4. Indexes of Mode Innovation

The indexes of collaboration and interaction are as follows:

(a) Proportion of enterprises that achieve networked collaboration, which refers to the proportion of enterprises that have achieved networked collaboration among all above-scale discrete manufacturing enterprises. In our work, networked collaboration involves cross-enterprise networked collaborative product design, cross-enterprise networked manufacturing and so on.
(b) The proportion of enterprises that achieve service-oriented manufacturing, which refers to the proportion of enterprises that have achieved service-oriented manufacturing among all above-scale discrete manufacturing enterprises. In our work, service-oriented manufacturing involves online operation and maintenance, remote monitoring, precise networked marketing, innovative service provision on the basis of intelligent terminals and so on.

(c) Proportion of enterprises that achieve personalized customization, which refers to the proportion of enterprises that have achieved personalized customization among all above-scale discrete manufacturing enterprises. Enterprises achieving personalized customization are capable of arranging and optimizing productions automatically based on customer orders and material supply.

4.3. Weights of Indexes

As shown in Table 1, the monitoring index system for sectors’ DT includes 13 monitoring indexes. To score the overall level of a sector’s DT, a weight method of interval valued hesitant fuzzy entropy are explored here for weight assignment.

Analytic hierarchy process (AHP) can analyze the problems hierarchically and combines the evaluation indicators according to different levels [17]. However, the importance of judgment matrix depends entirely on expert experience with large subjective components and relatively large amount of calculation. When the relationship of elements is complex, principal component analysis (PCA) is a good choice [18]. However, principal component analysis may lose the original information, which will affect the final weight result.

The entropy weight method (EWM) determines weight according to the amount of information [19]. That is to say, the more comprehensive effect an element can play, the more weight it will obtain. However, the entropy weight method has no fuzziness. In practice, it is sometimes difficult to give an accurate value, so it is difficult to quantify the qualitative problem reasonably.

When scoring the importance of an element, experts may hesitate between several scores. The weight determined by interval hesitant fuzzy entropy can weaken the uncertainty of experts in subjective scoring [20], and further make the determination of evaluation weight more reasonable [21].

In this section, we use interval valued hesitant fuzzy entropy (IVHFE) to determine the weight of each index. The proposed monitoring index system can be depicted as a hierarchical structure as in Figure 3. IVHFE weakens the hesitation of experts’ subjective evaluation and calculates the first-level indexes and the second-level indexes respectively. A fuzzy model of interval optimization can determine the weights of all indexes more reasonably.

![Figure 3. Hierarchy of the proposed monitoring index system.](image)

The evaluation interval given by experts is an interval hesitant fuzzy element, and the set of these fuzzy elements is an interval fuzzy hesitant set.

If the expert \(q\) gives a scoring interval for index \(i\), the interval is \(Z(q) = [m,n]\). Then the interval hesitant fuzzy element of index \(i\) is:

\[
\tilde{g}_z(i) = \left\{ \left[ \tilde{g}_{z(q)}^{-}(i) \right], \left[ \tilde{g}_{z(q)}^{+}(i) \right]\right\},
\]

where \(\tilde{g}_{z(q)}^{-}(i)\) is interval left value \('m'\), \(\tilde{g}_{z(q)}^{+}(i)\) is interval right value \('n'\).
In the process of scoring, different experts have different understanding of the field and the depth of research. Therefore, when calculating the entropy of the interval hesitation fuzzy element, different experts should be given different weights \(w_q (w_q > 0)\). The interval hesitant fuzzy element, which is the score given by all experts for indicator \(i\), is substituted into (2) to calculate the interval hesitant fuzzy entropy:

\[
S_i = \frac{1}{\sqrt{2} - T} \sum_{q=1}^{T} \left( \sin \left( \frac{\delta z(q) + \delta z(T-q+1)}{4} \right) + \cos \left( \frac{\delta z(q) + \delta z(T-q+1)}{4} \right) - 1 \right),
\]

(2)

where \(T\) is the number of experts, \(z(q)\) is the score interval of the \(q\)th expert, \(S_i\) is the hesitant fuzzy entropy of the index \(i\). By calculating entropy values of all indexes at the same level, \(W_i\), the weight of the index \(i\), can be derived as follows:

\[
W_i = \frac{1 - S_i}{\sum_{i=1}^{N}(1 - S_i)},
\]

(3)

where \(N\) is the number of indexes at the same level, and we have: \(0 < W_i \leq 1\).

Table 2. Interval Hesitation Fuzzy Element of the First-Level Indicators.

| First-Level Indicators | Score |
|------------------------|-------|
| \(E_1\)                | \(E_2\) | \(E_q\) | \(E_T\) |
| A1 \((-1(A_1) - A_1)\) | \(S_{z(E_1)}\) | \(S_{z(E_2)}\) | \(S_{z(E_q)}\) | \(S_{z(E_T)}\) |
| A2 \((-A_2) - A_2\)    | \(S_{z(E_1)}\) | \(S_{z(E_2)}\) | \(S_{z(E_q)}\) | \(S_{z(E_T)}\) |
| A3 \((-A_3) - A_3\)    | \(S_{z(E_1)}\) | \(S_{z(E_2)}\) | \(S_{z(E_q)}\) | \(S_{z(E_T)}\) |
| A4 \((-A_4) - A_4\)    | \(S_{z(E_1)}\) | \(S_{z(E_2)}\) | \(S_{z(E_q)}\) | \(S_{z(E_T)}\) |

By substituting the interval hesitation fuzzy element to (2), the interval hesitation fuzzy entropy of the first-level indexes is obtained as \(S_A = \{S_{A_1}, S_{A_2}, S_{A_3}, S_{A_4}\}\). Then by (3), their weight values \(W_A = \{W_{A_1}, W_{A_2}, W_{A_3}, W_{A_4}\}\) can be calculated, see Table 3.

Table 3. Interval Hesitation Fuzzy Entropy and Weight of the First Level.

| Interval Hesitation Fuzzy Entropy | Weight |
|----------------------------------|--------|
| \(S_{A_1}\)                     | \(W_{A_1}\) |
| \(S_{A_2}\)                     | \(W_{A_2}\) |
| \(S_{A_3}\)                     | \(W_{A_3}\) |
| \(S_{A_4}\)                     | \(W_{A_4}\) |

According to (3), we can obtain:

\[
W_A = \sum_{i=1}^{4} W_{A_i} = 1.
\]

(4)

The weight calculation of the second-level indicators is similar to that of the first-level indicators. The interval hesitation fuzzy element of the second-level indicators is substituted into (2) to obtain the corresponding set of interval hesitation fuzzy entropy. The sets of interval hesitation fuzzy entropy of the indicators in the second level are as follows: \(S_{A_1B} = \{S_{B_1}, S_{B_2}, S_{B_3}, S_{B_4}\}\), \(S_{A_2B} = \{S_{B_5}, S_{B_6}, S_{B_7}\}\), \(S_{A_3B} = \{S_{B_8}, S_{B_9}, S_{B_{10}}\}\), \(S_{A_4B} = \{S_{B_{11}}, S_{B_{12}}, S_{B_{13}}\}\). Substituting the calculated interval hesitation fuzzy entropy into (3), the corresponding set of weight values \(W_{AB} (i = 1, \ldots, 4)\) is obtained.
The weight $W_{A_i}$ of the first-level indicator $A_i$ to the target problem is recorded as $a_i$ ($i = 1, \ldots, 4$), and the weight $W_{A_iB_j}$ of the second-level indicator $B_j$ directly connected to the first-level indicator $A_i$ relative to its upper-level indicator $A_i$ is recorded as $b_{ij}$ ($j = 1, \ldots, 13$).

Then the weight of the second-level indicator $B_j$ relative to the target problem is $a_i b_{ij}$. According to (3), we can obtain

$$\sum_{i=1}^{4} \sum_{j=1}^{t} W_{A_i} W_{A_iB_j} = \sum_{i=1}^{4} \sum_{j=1}^{t} a_i b_{ij} = 1,$$

(5)

where $t$ is the number of the second-level indicators corresponding to the first-level indicator $A_i$. According to (5), we know that the sum of the weights of indicators on the second level relative to the target problem is 1.

The weights of indicators on the second level relative to the target question are shown in Table 4.

**Table 4. Weight Values of the Second-Level Indexes.**

| Second-Level Indicators | Weight | Second-Level Indicators | Weight |
|-------------------------|--------|-------------------------|--------|
| B1                      | $a_1 b_{11}$ | B8                     | $a_3 b_{38}$ |
| B2                      | $a_1 b_{12}$ | B9                     | $a_3 b_{39}$ |
| B3                      | $a_1 b_{13}$ | B10                    | $a_3 b'_{510}$ |
| B4                      | $a_1 b_{14}$ | B11                    | $a_4 b_{411}$ |
| B5                      | $a_2 b_{25}$ | B12                    | $a_4 b_{412}$ |
| B6                      | $a_2 b_{26}$ | B13                    | $a_4 b_{413}$ |
| B7                      | $a_2 b_{27}$ |                        |        |

4.4. Methods and Steps for Calculation

In the monitoring index system for sectors’ DT, the score of every index and the overall level can be calculated as three steps, as shown in Figure 4.

**Figure 4. Calculation steps for the score of a sector’s digital transformation.**

4.4.1. Data Collected from Sample Enterprises

To monitor sectors’ DT and collect sample data, we developed the Contemporary Service Platform of Integration of Industrialization and Industrialization (www.cspiii.com, accessed on 31 August 2020) [59]. According the monitoring index system of DT, combined with sector characteristics, a set of questionnaires is designed for data collection from enterprises, which includes numerical questions, single choice questions, and checklist questions.

For numerical questions, the scoring can be calculated by the formula: $X_i = \frac{V_i - V_{min}}{V_{max} - V_{min}} \times 100$. Where $X_i$ means the score of this data collection item, which of value is between 0 and 100; $V_i$ means the real value of the ith data collection item; $V_{min}$ and $V_{max}$ are the minimum and maximum thresholds of this data collection item respectively.
For single choice questions, the scoring is calculated as follows:
(i) all the available options should be assigned with certain scores, which should be
distributed in the value between 0 and 100.
(ii) the score of the data collection items should be the corresponding score of the
selected option.

For checklist questions, the scoring is calculated as follows:
(i) all the available options should be assigned with certain scores, which should be
distributed in the value range of [0, 100], and the options’ total scores should be 100.
(ii) the score of the data collection items should be the sum of the selected options’ scores.

4.4.2. Score of Each Index of a Sector

The calculation methods for the value of each index are shown in Table 5. Normalization
is used here to transform the index value to the score of the index ranged in [0, 100].

| Monitoring Indexes                                      | Data Collection Method         | The Calculation Method                                                                 |
|--------------------------------------------------------|--------------------------------|---------------------------------------------------------------------------------------|
| Digital rate of production equipment                    | Numerical question             | The arithmetic mean of data collection items for all sample enterprises.               |
| Digital R&D tool application rate                       | Numerical question             | The arithmetic mean of data collection items for all sample enterprises.               |
| Numerical control (NC) rate of key processes            | Numerical question             | The arithmetic mean of data collection items for all sample enterprises.               |
| E-commerce application rate                             | Checklist question             | The proportion of sample enterprises that fill in the data collection items.            |
| Proportion of enterprises that achieve the integration  | Checklist question             | The proportion of sample enterprises that fill in the data collection items.            |
| of design and manufacturing                             |                                |                                                                                       |
| Proportion of enterprises that achieve integration of   | Checklist question             | The proportion of sample enterprises that fill in the data collection items.            |
| supply production-sale                                  |                                |                                                                                       |
| Proportion of enterprises that achieve integration of   | Checklist question             | The proportion of sample enterprises that fill in the data collection items.            |
| management and control                                  |                                |                                                                                       |
| Proportion of enterprises that achieve the control of   | Checklist question             | The proportion of sample enterprises that fill in all three data collection items.      |
| the whole lifecycle of products                         |                                |                                                                                       |
| Proportion of enterprises that achieve the collaboration| Checklist question             | The proportion of sample enterprises that fill in all two data collection items.        |
| over the industry chain                                 |                                |                                                                                       |
| Smart manufacturing readiness rate                      | Numerical question/Checklist    | Proportion of enterprises whose NC rate in key processes exceeds 50 percent and have almost completed integration of management and control as well as that of supply production-sale. |
| Proportion of enterprises that achieve networked       | Checklist question             | The proportion of sample enterprises that fill in the data collection items.            |
| collaboration                                           |                                |                                                                                       |
| Proportion of enterprises that achieve service-oriented | Checklist question             | The proportion of sample enterprises that fill in all three data collection items.      |
| manufacturing                                           |                                |                                                                                       |
| Proportion of enterprises that achieve personalized    | Checklist question             | The proportion of sample enterprises that fill in the data collection items.            |
| customization                                           |                                |                                                                                       |

4.4.3. Total Weighted Score of a Sector

The total score of a sector’s DT is derived by performing a weighted summation of all
indexes with the weights in Table 4.

This score can be regarded as an objective evaluation result of the DT level of a
sector. By continuously tracking the score of the monitoring index system, it is possible to
effectively judge and predict the development degree and trend of the sector’s DT.
5. Monitoring and Analysis for Sectors’ Digital Transformation in China

5.1. Data Source and Description of Samples

All data to be analyzed were collected from the Contemporary Service Platform of Integration of Industrialization and Industrialization (www.cspiii.com, accessed on 31 August 2020) [59]. By the end of June 2018, 99,910 enterprises in China had reported their DT data through the platform, accounting for 26.4% of the total number of industrial enterprises above designated size in the national statistical system. Moreover, this sample covers 31 provinces (cities) and 101 industries of China, which are capable of objectively representing and reflecting the overall status of sectors’ DT in China.

In terms of enterprises distribution in different sectors, the number of sample enterprises in machinery, food industry, and light industry was relatively large, accounting for 21.2%, 11.9%, and 11.9%, respectively, followed by electronics, building materials, textiles, petrochemistry, and transportation equipment manufacturing, all of the proportions of which exceeded 5%. This distribution was roughly consistent with the distribution of industries that occupy relatively large proportions such as machinery, light industry, food industry, textiles and building materials. The sample enterprises were of high representativeness for industries and can objectively reflect the DT level in China (See Figure 5).

![Figure 5. Sector representativeness of sample enterprises.](image)

In terms of size distribution, large-sized enterprises accounted for 6.5%, small- and micro-sized enterprises accounted for 58.7%, and medium-sized enterprises accounted for 17.8%. Compared with the distribution of industrial enterprises above designated size in China, the proportion of small- and micro-sized industrial enterprises in the samples was slightly lower, while the proportion of large and medium-sized industrial enterprises was higher (See Figure 6).

![Figure 6. Scale representativeness of sample enterprises.](image)
In terms of region distribution, largest number of sample enterprises was found in East China, reaching as high as 34.4%, followed by those in North and South China, which took up 20.3% and 14.1%, respectively. Compared with the distribution of industrial enterprises above designated size in China by regions, the proportions of sample industrial enterprises in East and North China were different from the actual distribution in national statistics, while the distribution in other regions was basically the same (See Figure 7).

![Figure 7. Region representativeness of sample enterprises.](image)

5.2. Overview of Sectors’ Digital Transformation in China

The level of sectors’ DT in China in 2018 reached 53.0. The application of ICT technology in some specific sectors, multi-business and multi-link integrated application and intelligent collaborative application is being continuously expanded horizontally and vertically.

From the perspective of enterprise size, the digitalization level of large enterprises remaining in the lead and growing stably, while that of small- and micro-sized enterprises and private enterprises improving rapidly, whose growth rates have exceeded that of large- and medium-sized enterprises (See Figures 8 and 9). The overview of sectors’ DT in China (2018) can be seen in Table 6.

![Figure 8. Digital transformation level of enterprises of different sizes.](image)

| Monitoring Priorities | Monitoring Indicators | Large-Sized Enterprises | Medium-Sized Enterprises | Small-Micro Enterprises | Overall Level |
|----------------------|-----------------------|-------------------------|-------------------------|------------------------|---------------|
|                      | single-domain digitalization | Digital rate of production equipment | 50.5% | 44.5% | 35.3% | 45.9% |
|                      |                       | Digital R&D tool application rate | 82.9% | 74.8% | 58.5% | 67.4% |
|                      |                       | Numerical control (NC) rate of key processes | 57.1% | 45.3% | 30.5% | 48.4% |
|                      |                       | E-commerce application rate | 67.8% | 61.0% | 53.1% | 58.8% |
|                      | integration and interconnection | Proportion of enterprises that achieve the integration of design and manufacturing | - | - | - | - |
|                      |                       | Proportion of enterprises that achieve integration of supply production-sale | 47.9% | 35.7% | 24.4% | 24.7% |
|                      |                       | Proportion of enterprises that achieve integration of management and control | 36.6% | 25.9% | 20.2% | 20.4% |

Table 6. Overview of Sectors’ Digital Transformation in China (2018).
Figure 8. Digital transformation level of enterprises of different sizes.

Figure 9. Annual growth of digital transformation of enterprises of different sizes.

Table 6. Overview of Sectors’ Digital Transformation in China (2018).

| Monitoring Priorities          | Monitoring Indicators                          | Large-Sized Enterprises | Medium-Sized Enterprises | Small-Micro Enterprises | Overall Level |
|--------------------------------|------------------------------------------------|-------------------------|--------------------------|-------------------------|---------------|
|                                | Digital rate of production equipment           | 50.5%                   | 44.5%                    | 35.3%                   | 45.9%         |
|                                | Digital R&D tool application rate              | 82.9%                   | 74.8%                    | 58.5%                   | 67.4%         |
|                                | Numerical control (NC) rate of key processes  | 57.1%                   | 45.3%                    | 30.5%                   | 48.4%         |
|                                | E-commerce application rate                    | 67.8%                   | 61.0%                    | 53.1%                   | 58.8%         |
| single-domain digitalization   | Proportion of enterprises that achieve the integration of design and manufacturing | -                       | -                        | -                       | -             |
| integration and interconnection| Proportion of enterprises that achieve integration of supply production-sale | 47.9%                   | 35.7%                    | 24.4%                   | 24.7%         |
|                                | Proportion of enterprises that achieve integration of management and control | 36.6%                   | 25.9%                    | 20.2%                   | 20.4%         |
| Collaboration and interaction  | Proportion of enterprises that achieve the control of the whole lifecycle of products | -                       | -                        | -                       | -             |
|                                | Proportion of enterprises that achieve the collaboration over the industry chain | 13.1%                   | 10.0%                    | 7.8%                    | 7.8%          |
|                                | Smart manufacturing readiness rate             | 7.0%                    | 7.0%                     | 7.0%                    | 7.0%          |
| Mode innovation                | Proportion of enterprises that achieve networked collaboration | 33.7%                   | 33.7%                    | 33.7%                   | 33.7%         |
|                                | Proportion of enterprises that achieve service-oriented manufacturing | 24.7%                   | 24.7%                    | 24.7%                   | 24.7%         |
|                                | Proportion of enterprises that achieve personalized customization | 7.6%                    | 7.6%                     | 7.6%                    | 7.6%          |
Seen from key indicators, the overall DT level of key areas in China has improved continuously, and the process of digitization, networkization and intelligentization has continuously accelerated. In terms of underlying devices, the digitalization rate of production equipment in China reached 45.9% in 2018, with grown 4.1% compared with that in 2016. In terms of R&D design, the digital R&D tool application rate in China reached 67.4% in 2018, having grown 9.1% compared with 2016. In terms of production control, China’s NC rate in key processes reached 48.4% in 2018, having grown 5.7% compared with 2016. In terms of intelligentization development, China’s intelligent manufacturing readiness rate was as high as 7.0% in 2018, having grown 37.3% compared with 2016 (see Figure 10).

5.3. Different Paths of Digital Transformation Taken by Major Sectors in China

The DT development level in different industries are not the same in China, and different development needs and production characteristics exist in different industries. Based on their respective urgent demands of digitalization, networkization, and intelligentization, different industries have launched active explorations with different focuses on integrated development, and taken the core problems and shackles found them in the process to be focuses to make breakthroughs in future development.

The DT level of different industries ranked from high to low were electricity, tobacco industry, electronics, transportation equipment manufacturing, petrochemistry, pharmaceutical industry, textiles, machinery, light industry, food industry, metallurgy, building materials, and mining industry, presenting an overall status that the DT level of energy industry was higher than that of the manufacturing industry, and the latter was higher than that of mining industry. For the manufacturing industry, the DT level of consumer goods and electronics industries were relatively high, which were also higher than China’s national average, and the level of raw materials and equipment industries were basically the same (See Figure 11).
on integrated development, and taken the core problems and shackles found them in the process to be focuses to make breakthroughs in future development.

The DT level of different industries ranked from high to low were electricity, tobacco industry, electronics, transportation equipment manufacturing, petrochemistry, pharmaceutical industry, textiles, machinery, light industry, food industry, metallurgy, building materials, and mining industry, presenting an overall status that the DT level of energy industry was higher than that of the manufacturing industry, and the latter was higher than that of mining industry. For the manufacturing industry, the DT level of consumer goods and electronics industries were relatively high, which were also higher than China’s national average, and the level of raw materials and equipment industries were basically the same (See Figure 11).

The equipment industry takes the innovative application of digital R&D tools as a breakthrough point to promote DT [60], which is one of the most promising areas for integrated development among different industries [61]. The raw material industry represented by the petrochemistry focuses on strengthening the level of intelligentization in the manufacturing process, thus remaining at the lead among different industries in terms of the digital rate of production equipment, the networked rate of digital production equipment and the readiness rate of intelligent manufacturing [62]. The consumer goods industries, such as the food industry, pharmaceutical industry, etc. focuses on creating a rapid response capability to user needs, whose industry chain has a high level of coordination [63]. The electronics industry focuses on promoting the intelligentization development of products, whose levels of digitalization, networkization and intelligentization of product R&D, production and manufacturing are among the highest in all industries (see Figure 12).

Figure 11. Overview of sectors’ digital transformation in China.

The equipment industry takes the innovative application of digital R&D tools as a breakthrough point to promote DT [60], which is one of the most promising areas for integrated development among different industries [61]. The raw material industry represented by the petrochemistry focuses on strengthening the level of intelligentization in the manufacturing process, thus remaining at the lead among different industries in terms of the digital rate of production equipment, the networked rate of digital production equipment and the readiness rate of intelligent manufacturing [62]. The consumer goods industries, such as the food industry, pharmaceutical industry, etc. focuses on creating a rapid response capability to user needs, whose industry chain has a high level of coordination [63]. The electronics industry focuses on promoting the intelligentization development of products, whose levels of digitalization, networkization and intelligentization of product R&D, production and manufacturing are among the highest in all industries (see Figure 12).

5.4. There Exists Imbalance among Different Regions in China

It is obvious that the DT level in various provinces in China shows a hierarchical distribution, with an overall status of “high in the coastal areas and southwest, low in the northwest and the northeast”. Due to the differences in strategy orientation, economic foundation, industrial structure, and resource endowment, etc., the DT levels of different provinces have obvious hierarchical distribution characteristics overall. Among them, provinces and cities in the first class include Shandong, Shanghai, Jiangsu, Guangdong, Beijing, Chongqing, Tianjin, Fujian, Zhejiang, Sichuan, etc., which are mostly located in the eastern coastal area, while Sichuan and Chongqing are always the pioneers in the southwest region. The provinces and cities in the second class are located intensively in the center and east of China such as Hebei, Liaoning, Hubei, Henan, Anhui, Inner Mongolia, Shanxi, Shaanxi, Jiangxi, Jilin, Hunan, etc. The third class involves provinces and cities
scattered in the northeast and northwest China, including Ningxia, Heilongjiang, Guizhou, Guangxi, Hainan, Qinghai, Gansu, Tibet, Xinjiang, etc. (See Figure 13).

| Region                         | DT Level | Machinery | Automotive | Building | Steel | Petrochemical | Light | Food | Pharmaceutical |
|-------------------------------|----------|-----------|------------|----------|-------|---------------|-------|------|----------------|
| Equipment Industry            | Low      | 81.1%     | 39.7%      | 31.1%    |        |               |       |      |                |
| Raw material Industry         | Low      | 54.9%     | 45.6%      | 40.5%    |        |               |       |      |                |
| Consumer goods industry       | Low      | 68.4%     | 42.1%      | 34.1%    |        |               |       |      |                |
| Electronics Industry          | Low      | 78.3%     | 53.6%      | 44.2%    |        |               |       |      |                |
| Application rate of digital R&D design tools | High | 85.9% | 42.3% | 40.5% | 9.7% | 7.4% | 8.4% |
| Digitalization rate of production equipment | High | 51.8% | 49.2% | 7.1% | 5.4% |
| Networked rate of digital production equipment | High | 58.0% | 54.2% | 33.5% | 8.3% | 9.8% |
| Resilience rate of intelligent manufacturing | High | 65.5% | 48.0% | 39.2% | 6.6% | 10.6% |
| Proportion of enterprises that have realized collaboration in the industrial chain | High | 57.6% | 46.4% | 36.2% | 6.6% | 10.6% |

Figure 12. Key indexes of digital transformation of China’s major sectors.

![Data map of China’s regional digital transformation](image)

Figure 13. Data map of China’s regional digital transformation.

6. Prediction of Sectors’ Digital Transformation in China

Depending on the history data regarding the DT level in China over the past several years, a gray forecasting model is explored to predict the level in next few years with both known information and uncertainty.

This is a time-related predictive problem that changes within a certain range. Because the function form is unknown, it is difficult to establish an accurate mathematical model. In addition, it is inappropriate to use artificial neural network because the amount of data is small. Gray forecasting model is a kind of forecasting method that uses a small amount of incomplete information to establish a mathematical model and make predictions. Therefore, we use gray forecasting model to predict the level of sectors’ DT in the next few years based on historical data about the level of sectors’ DT in the current year and the previous years.

As shown in Figure 14, a statistical analysis of existing historical data shows that the
scores of sectors’ DT are increasing year by year, while the growth rates generally tend to slow down. Therefore, a gray prediction can be made as follows:

(a) Feasibility analysis of gray prediction
To ensure the feasibility of the GM (1, 1) modeling method, it is necessary to perform necessary inspections on the known data. Let the original data be listed as:

\[ x^{(0)} = \left( x^{(0)}(1), x^{(0)}(2), \ldots, x^{(0)}(n) \right). \]  \hspace{1cm} (6)

Among this equation, \( n \) is 9, and \( x^{(0)} \) is the scores of sectors’ DT from 2012 to 2020. Calculate the grade ratio of the sequence:

\[ \lambda(k) = \frac{x^{(0)}(k-1)}{x^{(0)}(k)}, k = 2, 3, \ldots, n. \]  \hspace{1cm} (7)

All the grade ratios fall within the acceptable coverage interval \( X = \left( e^{\frac{a}{n+1}}, e^{\frac{b}{n+1}} \right) \), so the sequence \( x^{(0)} \) can be modeled with GM(1, 1) model and the gray predictions can be made.

(b) Build the GM (1, 1) model

\[ x^{(0)}(k) + az^{(1)}(k) = b. \]  \hspace{1cm} (8)

Use regression analysis to obtain the estimated values of \( a \) and \( b \), calculate the superimposed sequence \( x^{(1)} \) from the original data sequence \( x^{(0)} \). So the corresponding whitening model is:

\[ \frac{dx^{(1)}(t)}{dt} + ax^{(1)}(t) = b. \]  \hspace{1cm} (9)

The solution is:

\[ x^{(1)}(t) = \left( x^{(0)}(1) - \frac{b}{a} \right) e^{-\alpha(t-1)} + \frac{b}{a}. \]  \hspace{1cm} (10)

The predicted value is as follows:

\[ \hat{x}^{(1)}(k + 1) = \left( x^{(0)}(1) - \frac{b}{a} \right) e^{-\alpha k} + \frac{b}{a}, k = 1, 2, \ldots, n - 1. \]  \hspace{1cm} (11)

The predicted value can be obtained accordingly:

\[ \hat{x}^{(0)}(k + 1) = \hat{x}^{(1)}(k + 1) - \hat{x}^{(1)}(k), k = 1, 2, \ldots, n - 1. \]  \hspace{1cm} (12)
(c) Prediction test

Calculate the relative residuals:

\[ \varepsilon(k) = \frac{x^{(0)}(k) - \hat{x}^{(0)}(k)}{x^{(0)}(k)}, k = 1, 2, \ldots, n. \]  

(13)

If all \(|\varepsilon(k)| < 0.1\), it is considered that the high requirements are met; otherwise, if all \(|\varepsilon(k)| < 0.2\), it is considered that the general requirements are met. In our work, the test value \(\varepsilon(k)\) of the score of sectors’ DT from 2012 to 2020 is 0.0024, so it can be considered that the prediction meets high requirements.

Based on the historical data on the level of sectors’ DT from 2012 to 2020, the score of sectors’ DT from 2021 to 2023 are predicted. We use MATLAB to calculate the gray prediction value as shown in Figure 15.

**Figure 15. Predication of sector’ digital transformation in China.**

From the above autoregressive prediction, the sectors’ DT level in China will keep growing in the future three years. The progress of multiple aspects leading to this result such as the single-domain digitalization, Integration and interconnection, Collaboration and interaction, mode innovation and other aspects will be enhanced in varying degrees.

7. Conclusions and Future Work

This study proposes a monitoring index system for sectors’ DT. Based on the data collected from 99,910 enterprises, an overview of development level and effect of China’s DT is derived. There are three main achievements:

(i) A monitoring index system for sectors’ DT is proposed on basis of the assessment framework of enterprises’ DT, which contains four aspects and 13 monitoring indexes. A weight method of interval valued hesitant fuzzy entropy is used for the weight assignment of all indexes in the monitoring index system.

(ii) An overview of China’s DT is derived by applying the monitoring index system with the monitoring data from 99,910 enterprises.

(iii) With the history data from 2012–2020, the prediction of sectors’ DT in China is transformed into a self-regression problem, and the predicted level for next three years is derived with gray prediction.

The implications of our work are multifold. Theoretically, fully considering the current development and potential needs of DT, we propose a monitoring index system, which provides evaluation criteria and guiding reference for the development of sectors’ DT. With the monitoring index system, on the one hand, it could help sectors carry out comprehensive and quantitative analysis of their current DT status; and on the other hand, the result of assessment could provide sectors with insights of future direction and feasible path of DT. Practically, our study takes China as an example to illustrate how to make full
use of the monitoring index system to monitoring sectors’ DT of a country, including the national overview, sectoral and regional differences, etc.

The future works of this study mainly focus on following two aspects:

(i) In the future improvement of the monitoring index system, we will optimize and expand the monitoring indexes, especially increasing the monitoring indexes directly reflecting the final value and benefit of DT.

(ii) We will implement some systematical analysis about the advantages and challenges of DT in other major countries by applying our monitoring index system.

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