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A novel model for assessing the degree of intelligent manufacturing readiness in the process industry: process-industry intelligent manufacturing readiness index (PIMRI)*

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Abstract: Recently, the implementation of Industry 4.0 has become a new tendency, and it brings both opportunities and challenges to worldwide manufacturing companies. Thus, many manufacturing companies are attempting to find advanced technologies to launch intelligent manufacturing transformation. In this study, we propose a new model to measure the intelligent manufacturing readiness for the process industry, which aims to guide companies in recognizing their current stage and short slabs when carrying out intelligent manufacturing transformation. Although some models have already been reported to measure Industry 4.0 readiness and maturity, there are no models that are aimed at the process industry. This newly proposed model has six levels to describe different development stages for intelligent manufacturing. In addition, the model consists of four races, nine species, and 25 domains that are relevant to the essential businesses of companies' daily operation and capability requirements of intelligent manufacturing. Furthermore, these 25 domains are divided into 249 characteristic items to evaluate the manufacturing readiness in detail. A questionnaire is also designed based on the proposed model to help process-industry companies easily carry out self-diagnosis. Using the new method, a case including 196 real-world process-industry companies is evaluated to introduce the method of how to use the proposed model. Overall, the proposed model provides a new way to assess the degree of intelligent manufacturing readiness for process-industry companies.

Key words: Process industry; Industry 4.0; Readiness model; Intelligent manufacturing; Readiness index
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1 Introduction

With the development of the fourth industrial revolution, worldwide industrial companies are trying their best to carry out intelligent manufacturing transformation, aiming at tackling the challenges of Industry 4.0 and staying competitive in the global market. However, Industry 4.0 covers a very wide range, which brings many difficulties to industrial companies during intelligent manufacturing transformation, such as where/how to start and what is the direction. A better understanding of the characteristics of Industry 4.0 is an indispensable step before proceeding with the intelligent manufacturing transformation.

The term Industry 4.0 was first proposed by Kagerman in 2011 to describe the widespread integration of information and communication technology in industrial manufacturing (Lin et al., 2019). Since then,

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many concepts have emerged (Stefan et al., 2018), including smart factory (Zuehlke, 2010), smart manufacturing (Kang et al., 2016), cyber-physical system (Wu et al., 2011), Industrial Internet of Things (IIoT) (Boyes et al., 2018), etc. Nevertheless, these concepts depict a similar thing to Industry 4.0. Acatech defined Industry 4.0 as "real-time, high data volume, multilateral communication and interconnectedness between cyber-physical systems and people" (Schuh et al., 2017). According to Dilberoglu et al. (2017) and Pereira and Romero (2017), Industry 4.0 is an umbrella term that comprises a set of future industrial developments regarding intelligent production systems and advanced information technologies. Overall, we agree that Industry 4.0 is a new paradigm in which people, the physical system, and the information system are systematically connected based on digitization.

Compared with many developed countries, China got off a late start in the implementation of Industry 4.0, but has achieved a fast development in intelligent manufacturing transformation. The World Economic Forum and McKinsey have selected 103 "Global Lighthouse Factories," 37 of which are Chinese manufacturing companies (World Economic Forum, 2022). There is no doubt that these lighthouse factories could provide a good reference for other manufacturing companies. However, for large quantities of traditional factories, especially small- and medium-sized enterprises (SMEs), there is a huge gap between them and these lighthouse factories. The biggest problem is that they could not simply copy their construction roadmaps; therefore, the development level of lighthouse factories becomes only a goal that is unattainable to some extent.

To help these SMEs overcome the dilemma of intelligent manufacturing transformation, the governments, academic institutions, and some leading companies all over the world proposed various models to evaluate the degree of Industry 4.0 readiness and maturity for them. By reviewing relevant literature, it is found that the distinction between readiness and maturity is not obvious (Pacchini et al., 2019). Some models generally treat readiness and maturity as synonyms. Notably, readiness is different from maturity. Schumacher et al. (2016) thought that readiness aims to capture the starting point and allow for initializing the development process, whereas maturity captures the as-it-is state while maturing the process. In addition, many scholars have stated that readiness assessment should take place before the maturation process (Schumacher et al., 2016; Pacchini et al., 2019). In conclusion, the maturity model aims to evaluate the current state of an industrial company in its implementation of Industry 4.0, whereas the readiness model focuses mainly on the necessary abilities that should be obtained to reach a certain maturity state. Therefore, developing a useful readiness model is the first and most important step to help a company reach a higher maturity level in the process of intelligent manufacturing.

At present, the proposed readiness models basically target all types of industrial organizations and enterprises, but they neglect that there is a huge gap in daily operations among different industries. Different industries have their own characteristics, and they are not suited for all "enabling technology" applications. Moreover, some models regard the number of and the degree of applications of "enable technologies" as the reference to assess the degree of Industry 4.0 implementation, and yet this violates that the essence of a manufacturing company is the production unit. Excessive focus on top-level design and new technology application would lead to disconnection from the reality of production. When using these models to evaluate the readiness of a company, some dimensions would rank low in the inadaptable areas, and as a result, the evaluation results likewise made little sense for the company. Verband Deutscher Maschinen- und Anlagenbau (VDMA) reported that Industry 4.0 readiness refers to "the willingness and capacity of companies to implement the ideas behind Industry 4.0" (Lichtblau et al., 2015). Indeed, it is important to include organization and people's ability when designing a readiness model. We also recognize that the top-level design and underlying infrastructure construction situation should both be taken into account. In addition, focusing on one specific industry could increase the accuracy of a readiness model. This makes the measurement of a degree of readiness for process industry an interesting research gap to be explored in this study.

This work aims to measure the degree of process-industry intelligent manufacturing readiness in relation to the implementation of Industry 4.0. In this paper, a novel readiness model targeting the process industry is proposed, and based on this model, the readiness index is further created. Finally, an example case using the presented assessment approach is discussed in a real-world company to display its transparency and practicability.

2 Literature review

2.1 Intelligent manufacturing

Intelligent manufacturing is a broad concept that is constantly changing as abundant advanced technologies have developed (Holubek and Kostal, 2013). Wright and Bourne (1988) first proposed the term "intelligent manufacturing," which is defined as follows: "By integrating knowledge engineering, manufacturing software systems, robot vision, and robot control, experts' knowledge and workers' skills are modeled to enable intelligent machines to perform small-scale production without human intervention." Since the beginning of the 21st century, information technology has developed vigorously, triggering many new technologies, such as cloud computing, big data, the Internet of Things, the mobile Internet, digital twins, and artificial intelligence (Li et al., 2017; Oztemel and Gursev, 2020; He and Bai, 2021). As a result, these new technologies provide more possibilities for the implementation of intelligent manufacturing. It is well known that digitization is the precondition to realize intelligent manufacturing. Wang LH (2019) commented that intelligent manufacturing depends on the timely acquisition, distribution, and utilization of real-time data from both machines and processes on manufacturing shop floors and even across product life cycles.

In an intelligent manufacturing system, the key process state can be monitored precisely, thereby acquiring a large amount of data in a timely manner. The obtained data are then managed and analyzed based on historical and practical experience to direct the manufacturing process to realize flexible process control (Wang BC et al., 2021). Additionally, the intelligent manufacturing system could make a quick response according to the diverse and personal requirements with the minimum environmental damage. Many countries have reported their strategic plans to guide industrial companies carrying out intelligent manufacturing transformation, including Industry 4.0 in Germany, the Industrial Internet of Things (IIoT) in the United States, and the Industrial Value Chain Initiative (IVI) in Japan (Zhong et al., 2017). Similarly, the Chinese government proposed the concept of the integration of industrialization and informatization, which illustrates five characteristics of intelligent manufacturing: self-perception under depth information, self-execution under precise control, self-decision under intelligent optimization, self-learning under rule discovery, and self-adaptation of a complex environment. Intelligent manufacturing built on digitalization is also intended to be more sustainable and to contribute to industrial companies in the future.

2.2 Readiness/maturity model review

As mentioned before, the concept of Industry 4.0 was developed in Germany, and they proposed a maturity model and a readiness model in 2015 and 2017, respectively. The readiness model was created by VDMA, which was used to define criteria through which companies were classified into three types: "newcomers," "learners," and "leaders." This classification was based on the following six key dimensions of Industry 4.0: strategy and organization, smart factory, smart operations, smart products, data-driven services, and employees (Lichtblau et al., 2015). The maturity model was intended to provide informed assessments and future-oriented advice for policymakers and society about Industry 4.0 (Schuh et al., 2017). Meanwhile, the Singapore Economic Development Board (SEDB) proposed a smart industry readiness index (SIRI) in 2017 (Singapore Economic Development Board, 2017). This model was a three-layer structure that includes 3 building blocks, 8 pillars, and 16 dimensions. After two years of application, the SEDB found that many companies have recognized their Industry 4.0 readiness levels, but many of them were unable to translate their acquired knowledge to actionable transformation plans. Therefore, the SEDB proposed a prioritization matrix model (TIER) to help the companies identify focus areas and make an overall Industry 4.0 roadmap. These three models are the most popular readiness and maturity models in Industry 4.0, which also gave us a lot of inspiration to design the new readiness model.

Since 2011, many scholars have made efforts to develop an assessment model for Industry 4.0. Angreani et al. (2020) performed a systematic literature review of empirical studies implemented on the maturity model published in several reputable and relevant sources to study the model dimensions and application sectors. They found that technological, operational dimensions, leadership, and culture were the most considered dimensions. Hizam-Hanafiah et al. (2020) reviewed 30 Industry 4.0 readiness models with 158 unique model dimensions. They concluded that the technology dimensions occupied the main position for future research on Industry 4.0 readiness. In addition, we illustrate the reported readiness and maturity models for Industry 4.0 in Tables 1 and 2, respectively. Moreover, the information of the model structure and its main dimensions are listed for comparison, thereby providing some reference to the newly proposed readiness model in Section 3.1.

Table 1 List of readiness models for Industry 4.0

Model name	Year	Model structure	Main dimensions	Reference
Readiness model for the implementation of Industry 4.0	2019	Measure 7 enable technologies in 6 readiness levels	IoT, big data, cloud computing, cyber-physical system, autonomous robot, additive manufacturing, augmented reality	Pacchini et al., 2019
Industry 4.0 readiness evaluation for manufacturing enterprises	2019	Seven levels for Industry 4.0 within Society 4.0	Society, area of society, branch of area of society, enterprise, area of enterprise, dimensions of enterprise area, subdimensions of enterprise area	Basl and Doucek, 2019
Future readiness level (FRL)/Industry 4.0 future readiness	2018	Measure 4 dimensions in 10 readiness levels (behavior dimension has 5 levels) for future readiness	Technology, behavior, event, future thinking	Botha, 2018
E-business Industry 4.0 readiness model	2018	Measure 12 indicators in 3 subdimensions for Industry 4.0	eBusiness, ICT specialist, broadband take-up and coverage	Demeter et al., 2018
Readiness for Industry 4.0	2018	A multidimensional and multistage approach includes 5 dimensions in 4 stages	Technology, organization of production and logistics, management and strategy, employees and communication, interfirm cooperation	Horvat et al., 2018
Industry 4.0 readiness model for manufacturing	2018	Measure 7 dimensions and 31 subdimensions	Strategy, technology, manufacturing and operation, supply chain, employee, product, customer	Methavitakul and Santiteerakul, 2018
Industry 4.0 readiness model for tool management	2017	A three-step framework consists of 9 categories in 5 levels	Competencies, database integration, tool identification, time horizon of data analytics, location of data use, determining the residual tool life, degree of networking, IT-security, degree of standardization	Schaupp et al., 2017
Smart industry readiness index (SIRI)	2017	A three-layer structure includes 3 building blocks, 8 pillars, and 16 dimensions	Process, technology, organization	Singapore Economic Development Board, 2017
IMPULS-Industrie 4.0 readiness	2015	Measure 6 dimensions and 18 fields in 5 readiness levels	Strategy and organization, smart factory, smart operations, smart products, data-driven services, employees	Lichtblau et al., 2015
Roland Berger Industry 4.0 readiness index	2014	A readiness index model includes 2 categories and 8 dimensions	Industrial excellence: production process sophistication, degree of automation, workforce readiness, and innovation intensity; value network: high value added, industry openness, innovation network, and Internet sophistication	Blanchet et al., 2014

IoT: Internet of Things; ICT: information and communication technology; IT: information technology

Table 2 List of maturity models for Industry 4.0

Model name	Year	Model structure	Main dimensions	Reference
Smart SMEs 4.0 maturity model	2021	A two-layer structure includes 5 dimensions and 43 subdimensions	Business and organization strategies, technology-driven process, people capability, manufacturing and operations, digital support	Chonsawat and Sopadang, 2021
Maturity model of intelligent manufacturing capability	2020	A three-layer structure includes 4 capacity factors, 12 domains, and 20 subdomains	People, technology, resource, manufacture	GB/T 39116-2020
Industry 4.0 maturity model	2018	Measure 3 main dimensions and 13 key attributes in 4 levels	Factory of the future, people and culture, strategy	Bibby and Dehe, 2018
SMEs maturity model assessment of IR4.0 digital transformation	2018	Measure 6 dimensions in 6 levels	Employees, strategy and organization, smart factory, smart operations, smart product, data-driven service	Hamidi et al., 2018
Industry 4.0 maturity model	2018	Measure 3 dimensions, 5 subdimensions, and 13 fields	Smart products and services, smart business processes, strategy and organization	Akdil et al., 2018
Acatech Industrie 4.0 maturity index	2017	Measure 4 structural areas, and each area has two principles with the necessary capabilities	Resources, information system, organizational structure, culture	Schuh et al., 2017
Industry 4.0 maturity model-SPICE	2017	Measure 5 aspect dimensions in 6 capability dimensions (levels)	Asset management, data governance, application management, process transformation, organizational alignment	Gökalp et al., 2017
Three-stage maturity model in SMEs towards Industry 4.0	2016	A three-stage process model for Industry 4.0 projects	Envision, enable, enact	Erol et al., 2016
Industry 4.0 maturity model for manufacturing	2016	Measure 9 company dimensions and 62 maturity items	Strategy, leadership, customers, products, operations, culture, people, governance, technology	Schumacher et al., 2016

SPICE: software process improvement and capability determination; SMEs: small- and medium-sized enterprises

By comparing the readiness and maturity models listed in Tables 1 and 2, it can be found that most of them have different and complex structures. This is because they considered different application scenarios of Industry 4.0. However, after analyzing their main dimensions, it is interesting that they are all similar, indicating that the evaluation dimensions of Industry 4.0 are gradually coming to a consensus. In addition, two assessment directions can be concluded: one is focused on the enable technologies that are used in the manufacturing factories, and the other is focused on production and management in the manufacturing factories. After reviewing the readiness and maturity models above, we find that none of them focused on the process industry, which is also one of the highlights of our research scope.

2.3 Discussion on the problems of the listed readiness/maturity models

However, although many readiness/maturity models have been proposed, few publications have reported their real applications in intelligent manufacturing evaluation for industrial companies. In fact, there are some gaps between the theoretical model and real-world application. We conclude three main reasons that lead to this problem:

1. Most of the readiness/maturity models cover a wide range of different types of companies; in other

words, the models lack specificity. However, it is well known that there is a huge distinction between different industries among manufacturing factories, such as discrete industries and process industries. Therefore, it is difficult to evaluate the level of intelligent manufacturing for all types of factories using the same assessment model.

2. Many readiness/maturity models can only be used by designers or experts, leading to poor usability. A well-designed readiness/maturity model could provide a tool for industrial companies to carry out self-diagnosis.

3. The subjective thinking of the evaluator would disturb the accuracy of the evaluation result. Thus, it usually cannot reasonably reflect the requirements of intelligent manufacturing. Thus, collecting some hard evidence when processing measurement work should also be considered in the process of model designation.

From the above discussion, it is important to design a new readiness model to help manufacturing companies evaluate the level of intelligent manufacturing. These three reasons also provide a good reference for the model development process in Section 3.1.

3 Methods

3.1 Model development

Angreani et al. (2020) identified eight types of model development techniques: literature review, conceptual method, qualitative method, quantitative method, workshop, case studies, analytic network processing, and factory design and improvement. In this study, the structure and evaluated dimensions of the newly proposed model are designed using a literature review and conceptual method. Regarding the main dimensions in Tables 1 and 2, technology and organization are the two most frequently discussed dimensions. Indeed, technology is the major means of intelligent manufacturing implementation, whereas organization is a basic guarantee for orderly development. In addition, technology and organization must always serve for or be applied in tandem with an effective process, so that process is another dimension that should not be neglected. However, with the application of many new information systems in industrial companies, the phenomenon of "data island" gradually emerged. Individual information systems from different suppliers created barriers to data sharing to some extent. In addition, the repeated extraction of data from different systems would lead to the data storage burden. Furthermore, data collection, analysis, and utilization played an important role in further intelligent manufacturing transformation. Therefore, considering data governance and an integrated Internet platform becomes more imperative. That is what we want to evaluate in the "intelligence" dimension. Therefore, process, organization, technology, and intelligence are the four dominating dimensions in our proposed model, as introduced in Section 3.2.

Gökalp et al. (2017) supported that "the purpose, scope, elements, and indicators" should be defined when designing a model to guarantee the basic criteria of completeness–clearness–unambiguity. Therefore, we have formulated several principles to guide the readiness model development process, as shown in Table 3. Accordingly, in the model design process, these guiding principles are also followed, as explained in Table 3. Detailed information of the proposed model is introduced in Sections 3 and 4.

3.2 Readiness model

The process-industry intelligent manufacturing readiness index (PIMRI) refers mainly to the maturity model of intelligent manufacturing capability (GB/T 39116-2020) released by the Chinese State Administration for Market Regulation and Standardization Administration, which is the guidance document for intelligent manufacturing in China. The level distribution is the first part for the proposed model, whose level definitions are similar to those in GB/T 39116-2020, as shown in Fig. 1, including six levels as follows:

1. Level 0 (L0): initial level. A company at this level does not establish the relevant rules or regulations well. In other words, it does not meet any of the requirements for Industry 4.0.

2. Level 1 (L1): planning level. At this level, the company starts to make plans on the basis and conditions for implementing intelligent manufacturing. The core business activities, such as supply chain, production, products, and services, could be regulated using process management.

3. Level 2 (L2): canonical level. Digital equipment and information technologies are used to manage the core equipment and business activities at this level.

Table 3 Basic principles for the readiness model development

Principle	Description	The proposed model (PIMRI)	Principle	Description	The proposed model (PIMRI)
Object definition	The model should identify the specific object and be designed based on its characteristics	PIMRI targets at the process industry	Evaluation method description	The model should provide a complete description of the evaluation method	PIMRI gives a five-step method to carry out evaluation and the exhaustive calculation process
Level distribution	The model should make level distribution according to the stage of the object, and the corresponding requirements of different levels should be described in the context of Industry 4.0	PIMRI sets six readiness levels for intelligent manufacturing and defines the requirements for each readiness level	Objectivity of the evaluation method	The model should try to avoid the subjective factors of the evaluator and the evaluation object. In addition, the model should try to find the specific evidence in enterprise operation parameters, in practice, etc., for setting scores	During the evaluation process, experts carry out field research to find the reality of the enterprise operation and make the modifications
Completeness of dimensions	The model should cover exhaustive business activities during enterprise operation in the context of Industry 4.0	PIMRI consists of 4 races, 9 species, and 25 domains to evaluate enterprise readiness	Accessibility	The model should be easy to use when the enterprise carries out self-diagnosis	A questionnaire is designed according to the PIMRI
Granularity of subdimensions	The model should make the detailed explanations of the attributes in the corresponding dimensions	PIMRI further creates 249 characteristic items to give the detailed explanations for the 25 domains in different readiness levels			

PIMRI: process-industry intelligent manufacturing readiness index

Additionally, data sharing could be realized within one single business.

4. Level 3 (L3): integrated level. A company at this level carries out network integration of equipment and systems, and as a result, data sharing is realized across businesses.

5. Level 4 (L4): optimizing level. At the optimizing level, the company tries to collect the data of employers, equipment, products, the environment, and production. In addition, the model and knowledge are used to make predictions for core business activities and optimize the control process for partial business.

6. Level 5 (L5): leading level. When a company reached the leading level, it realized business optimization and continuous innovation based on a model-driven approach. New manufacturing and business models are created via industrial chain collaboration.

Fig. 1 Six levels of the process-industry intelligent manufacturing readiness model

Obviously, different levels require different necessary capabilities for a company when evaluating its intelligent manufacturing readiness. The overall company readiness index (R_o) has a corresponding relationship to the final readiness level, which is shown in Table 4. The calculation method of R_o is introduced in Section 3.3.

The process-industry intelligent manufacturing readiness model is shown in Fig. 2, which comprises four races (process, organization, technology, and intelligence) and nine species of focus, including supply chain, production management, technology management, human resources, organization management, infrastructure, integration interconnection, data-driven, and enable platform. These nine species are further divided into 25 domains of assessment that attempt to involve all areas in an enterprise's daily operations.

Moreover, each domain is further divided into several characteristic items corresponding to L1–L5, which represent the capabilities that should be occupied in this domain. Based on the 25 domains in Fig. 2, 249 characteristic items are finally created. For example, the characteristic items of operation management are shown in Table 5. Obviously, the operation management domain at different levels has several different requirements. To help the enterprise well understand the meaning of these characteristic items, we design some questions that are close to the enterprise's daily operations to reflect the characteristic items. An example of the questions for characteristic item 1 in L1 of warehouse management is listed in Table 6. It can be seen that the three questions are related to this characteristic item. In addition, each question has an individual weighting factor to calculate the characteristic item's readiness index. Except for the yes-or-no one-choice questions in Table 6, there are also other types of one-choice questions and multi-choice questions. For example, the characteristic item 2 in L2 of warehouse management requires that "a storage location (tank yard) management system should be established to realize the distribution of product storage location (storage tank), in-out warehousing and transfer (reladling), material measurement, etc.," and the corresponding questions are shown in Table 7.

3.3 Assessment approach

The process of readiness index evaluation in a company follows a five-step procedure, as shown in Fig. 3. First, a well-designed questionnaire needs to be completed by the target company. It is important that this questionnaire cannot be completed by only one person. The heads of different departments are responsible for their related field in the questionnaire, which could guarantee the accuracy of the answers to some extent. Next, we input all the answers

Table 4 The corresponding relation between R_o and the intelligent manufacturing level

L0: initial level	L1: planning level	L2: canonical level	L3: integrated level	L4: optimizing level	L5: leading level
$0<R_o<0.8$	$0.8 \le R_o<1.8$	$1.8 \le R_o<2.8$	$2.8 \le R_o<3.8$	$3.8 \le R_o<4.8$	$4.8 \le R_o \le 5.0$

R_o: the overall company readiness index

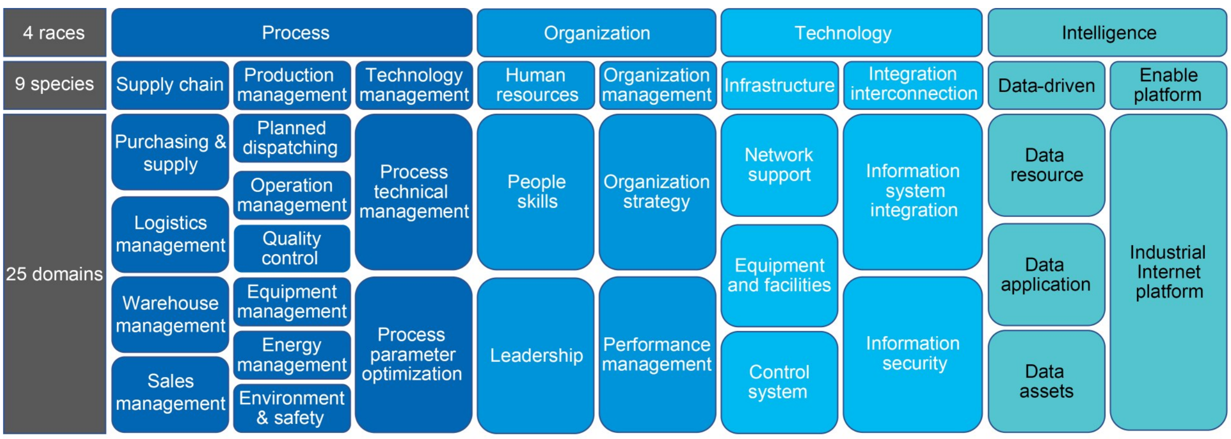

Fig. 2 The pocess-industry intelligent manufacturing readiness model

to a self-designed Excel document to calculate the readiness indexes of the characteristic items, domains, species, and races, and as a result, the overall company readiness index could also be obtained. In the third step, a group combined by the experts in different fields would go to the target company to hold an

Table 5 Characteristic items of operation management from L1 to L5

Level	Characteristic item(s)
L1	1. Relevant specifications for production operations should be formulated
	2. Operation training and inspection mechanism should be established
	3. Key information about the operation process should be recorded
L2	1. The record of the operation process should be collected via the information technology means and mobile terminal
	2. An information system should be established to control noncompliant operations and unauthorized operations
L3	1. Process system, production system, safety management system, and other systems should be integrated to form operational instructions and guide employees to operate
	2. Operational behaviors should be evaluated and accumulated to form the best operational behavior library
L4	1. The process optimization achievements should be used to guide operation
	2. The process operation knowledge library should be used to assist operators
	3. Virtual reality (VR) and augmented reality (AR) technologies should be used to assist and train operators
L5	1. Some pattern recognition technologies such as artificial intelligent (AI) technology should be used to assist operators in real time according to the process status

Table 6 Questions for the characteristic item 1 in L1 of warehouse management

Question	Option
Q1: Whether the enterprise has established the process operation procedure and standard operation procedure (SOP) document?	(1) Yes; (2) No
Q2: Whether the enterprise has established the process cards to stipulate the operating limits for key parameters?	(1) Yes; (2) No
Q3: Whether the visual images of standard operating procedures for on-site manual operations, such as equipment on-site operation and equipment maintenance, have been placed on the site?	(1) Yes; (2) No

Table 7 Questions for the characteristic item 2 in L2 of warehouse management

Question	Option
Q1[a]: What fields do the warehouse management system (WMS) cover?	(1) Covering the finished and semifinished product warehouse (2) Covering the accessory and consumable warehouse (3) Covering the raw material warehouse (4) Covering the spare parts and supply warehouse
Q2[b]: What the degree of automation of warehouse operations, that is, the proportion of warehouse operations, can be completed by automated equipment?	(1) 100%; (2) 60%; (3) 30%; (4) 0%

[a] Multi-choice question; [b] one-choice question

Fig. 3 Five-step procedure to assess intelligent manufacturing readiness

interview to check a more detailed and realistic situation. Then, the experts modified the readiness index of the characteristic items based on their related experience and the interview results. Finally, a visualization report that contains a line chart, radar chart, and histogram is created to help the company realize its current state and ascending direction in a more intuitive way.

The readiness index of the characteristic item is calculated by the following equation:

$$R_c = \frac{\sum_{i=1}^{n_q} S_{q,i}}{n_q}, \tag{1}$$

where $S_{q,i}$ represents the score of question i, n_q represents the number of questions in characteristic item c, and R_c represents the readiness index of characteristic item c.

The readiness index of the domain in level l (l=1, 2, ⋯, 5) is calculated by the following equation:

$$R_{d,l} = \frac{\sum_{i=1}^{n_c} R_{c,i}}{n_c}, \tag{2}$$

where n_c represents the number of characteristic items in domain d, level l, and $R_{d,l}$ represents the readiness index of domain d in level l.

The readiness index of the species in level l (l=1, 2, ⋯, 5) is calculated by the following equation:

$$R_{s,l} = \sum_{i=1}^{n_d} R_{d,l,i} \cdot g_{d,l,i}, \tag{3}$$

where n_d represents the number of domains in species s, $g_{d,l}$ represents the weighting factor of domain d in level l, and $R_{s,l}$ represents the readiness index of species s in level l.

The readiness index of the race in level l (l=1, 2, ⋯, 5) is calculated by the following equation:

$$R_{r,l} = \sum_{i=1}^{n_s} R_{s,l,i} \cdot g_{s,l,i}, \tag{4}$$

where n_s represents the number of species in race r, $g_{s,l}$ represents the weighting factor of species s in level l, and $R_{r,l}$ represents the readiness index of race r in level l.

The readiness index of the overall company in level l (l=1, 2, ⋯, 5) is calculated by the following equation:

$$R_{o,l} = \sum_{i=1}^{4} R_{r,l,i} \cdot g_{r,l,i}, \tag{5}$$

where $g_{r,l}$ represents the weighting factor of race r in level l, and $R_{o,l}$ represents the readiness index of the overall company in level l.

The weighting factor g is diverse in different evaluated aspects (domains, species, and races) of each readiness level. The setting criteria of g consider both requirements of different readiness levels and the importance of evaluated aspects in the process industry. After calculating the readiness indexes of domain, species, race, and the overall company in level l, their corresponding final readiness index is obtained by the following equation:

$$R_x = (l' - 1) + R_{x,l'}, \tag{6}$$

where x represents the domain, species, race, or overall company, and l' represents the first level number which is less than 0.8 from level 1 to level 5.

It seems a little difficult to understand the meaning of l', and thereby an example to calculate the readiness index of the overall company is displayed as follows. Table 8 shows the overall company index from level 1 to level 5. Obviously, in level 3, $R_{o,3}$ is the first one which is less than 0.8, so l' equals 3. Therefore, $R_o=(l'-1)+R_{o,l'}=(3-1)+0.60=2.60$.

Table 8 The readiness index of the overall company in levels 1–5

Level	Readiness index	Level	Readiness index
L1	$R_{o,1}$=0.90	L4	$R_{o,4}$=0.45
L2	$R_{o,2}$=0.86	L5	$R_{o,5}$=0
L3	$R_{o,3}$=0.60		R_o=2.60

4 Case and discussion

The PIMRI is designed to provide information not only for a company but also for the government, solution vendors, or some third-party consulting companies. In other words, the PIMRI is not merely a tool to help companies evaluate their intelligent manufacturing readiness by themselves. Actually, we consider that it could also help the government investigate the current development situation of the process industry and thereby formulate the related policy document, help the solution vendors develop and provide the corresponding solutions, and help the third-party consulting company issue the diagnosis report. To the best of our knowledge, the functions of the PIMRI can be divided into three aspects: process industry, a particular industry, and company evaluation. Next, an example is shown in the following to explain the specific applications in these three aspects.

4.1 Process industry overall evaluation

To show how the developed model could be applied in process-industry intelligent manufacturing readiness evaluation, a total of 196 Chinese process-industry companies have been selected and evaluated using this new approach. Based on the answers to the questionnaire and expert modification, the R_o values of these 196 Chinese process-industry companies are calculated, and their level distributions are displayed in Fig. 4. Apparently, more than half of the investigated companies are located at the planning level, while 71 companies belong to the canonical level. However, only four companies reach the optimizing level. These results indicate that there are quite large quantities of companies that are placed in the early stage of intelligent manufacturing.

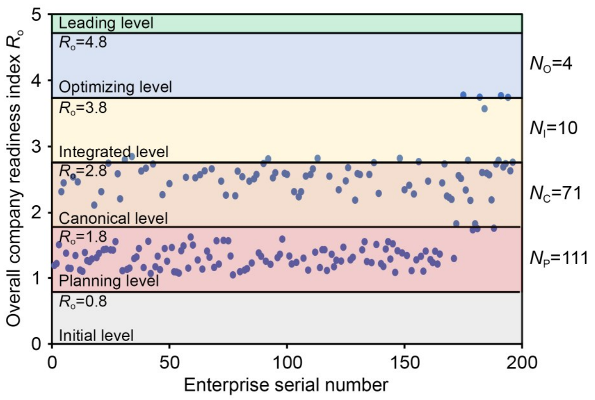

Fig. 4 Level distribution of the 196 Chinese process-industry companies

It is known that the process industry also includes many different types of industries. In this investigation, the 196 enterprises are divided into nine industries: metallurgical industry, building material industry, petrochemical industry, pharmaceutical industry, papermaking industry, salt chemical industry, fine chemical industry, coal chemical industry, and other industries. The exact distribution of each industry is shown in Fig. 5. Although they all belong to the process industry, their production equipment, process, key operation parameters, or other fields are sometimes far from each other. The reason for further subdivision is to let the evaluated company clearly understand the development situation of the same industry and find a leading company that is more similar to it as a reference. The experience of this leading company might be more helpful for this evaluated company as well as finding a more feasible way to carry out transformation and upgrading.

Fig. 6 exhibits the readiness index distribution of these nine specific industries. It is obvious that the metallurgical industry, building material industry, and petrochemical industry have better development compared with the other six industries. In detail, their best-level companies have reached the optimizing level, and the top 25% of companies are located at the integrated level and canonical level. There is no

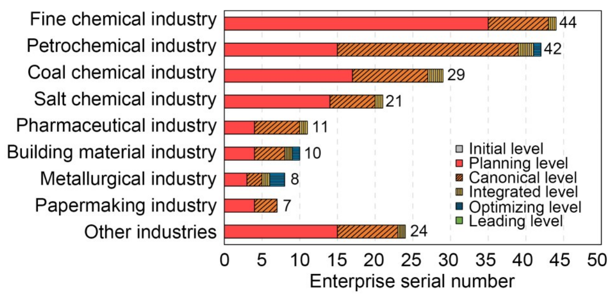

Fig. 5 Industry distribution of the 196 Chinese process-industry companies

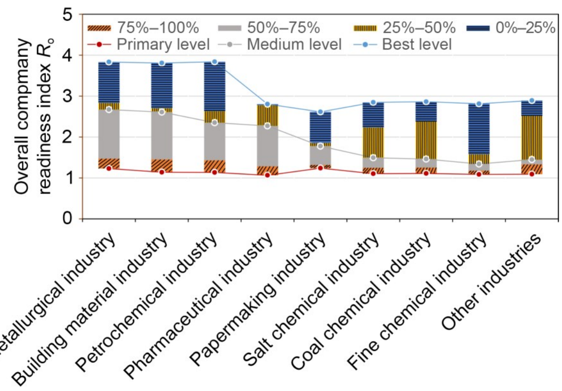

Fig. 6 Readiness index distribution of the 196 Chinese process-industry companies in nine specific industries (References to color refer to the online version of this figure)

doubt that these companies could play an exemplary role for others in their own industries. On the other hand, the gap between the best-level company and the primary-level company is large in these three industries. In the pharmaceutical industry, although the best-level company just reaches the integrated level, the readiness index is very close among the top 25% companies, indicating that the exemplary companies of the pharmaceutical industry equip the comparative balanced development situation. Particularly, it can be seen that the overall intelligent manufacturing readiness of the papermaking industry is relatively poor, but the tail companies achieve the best performance in the nine industries instead. There are three solid lines in Fig. 6, which represent the best, medium, and primary levels of each industry. The best level is the bellwether in their own industry, and the strategies for intelligent manufacturing transformation are to learn from the advanced theories and pay attention to the application practice of advanced technologies. Regarding the medium level, which represents the general development level of the industry, replicating the experience of the best level is the key point for the next construction. Finally, although the primary level is the lowest current situation of the industry, its development strategies are the easiest to make. Because many successful cases have been applied in other companies that belong to their industry, the primary-level companies could rapidly copy them with quick results.

In short, it can be seen that much information could be mined when using the PIMRI to evaluate the process industry, which could be beneficial for government and industry research companies in particular. However, to be honest, the sample size in this investigation is relatively small compared with the total number of process-industry companies in China or even in the world. Nonetheless, the above analysis of the 196 companies could provide an example to show how to use the PIMRI when conducting the process industry overall evaluation. In addition, the sample base will continue to be expanded, so that the analysis results would be more valuable.

4.2 A particular industry evaluation

The fine chemical industry is selected as an example to show how to use the PIMRI in a particular industry. The total number of fine chemical companies in this sample is 44, and their level distribution is shown in Fig. 7. The results show that 35 companies are located at the planning level, whereas only one company reaches the integrated level. Because most of the investigated companies are SMEs that are the sidelines of intelligent manufacturing, their overall readiness indexes are relatively poor.

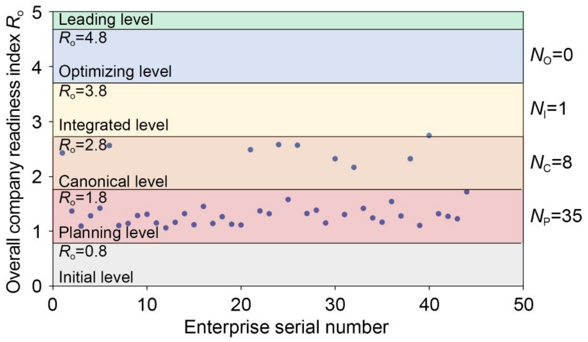

Fig. 7 Level distribution of the 44 companies in the fine chemical industry

The readiness indexes of race, species, and domain of these fine chemical companies are displayed in Fig. 8. For details, the four races perform comparably balanced so that neither one of the race is particularly prominent or laggard. As for the nine species in Fig. 8b, the R_s's of the technology management, organization management, and enable platform have better development among the top 25% companies compared with those of other species. Evaluating a particular industry readiness could not only determine the developing status of this industry but also build an industry database to help a company realize its position in the whole industry.

4.3 Company evaluation

To show how a company uses the PIMRI to analyze intelligent manufacturing capabilities by self-diagnosis, another fine chemical company out of the 196 evaluated companies was selected. The diagnosis results are displayed in Fig. 9. The overall company readiness index is 1.40, which belongs to the planning level. This indicates that the company has already formulated the regulations for the core business. Establishing the information system to realize data sharing in a single business is the transformation goal in the next step. For the nine species in Fig. 9b, infrastructure

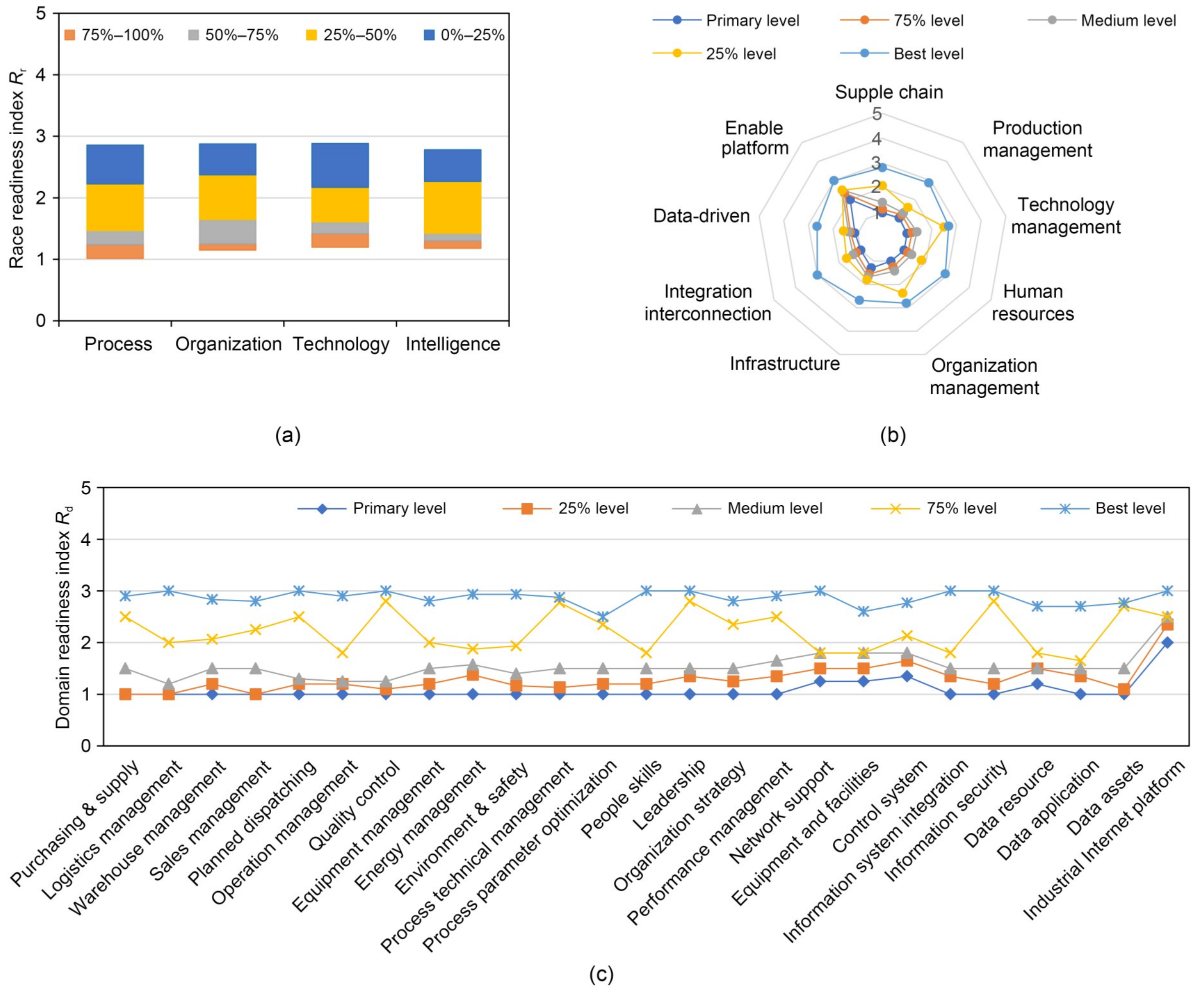

Fig. 8 Readiness index distribution of the 44 companies in the fine chemical industry: (a) race index R_r; (b) species index R_s; (c) domain index R_d

has a good foundation that nearly reaches the canonical level. In contrast, technology management and production management should be enhanced because these two species have fallen behind and become limiting factors when considering the construction of the upper level. Moreover, the target company has not yet begun to build an industrial Internet platform, leading to another obstacle for business integration.

To further reveal the target company's intelligent manufacturing readiness in the process industry and the fine chemical industry, the work of comparison is carried out with the results shown in Fig. 10. The readiness index of the target company is located in the range of 50%–75% of 196 process-industry companies and 25%–50% of 44 fine chemical industry companies. Usually, the position in the same industry sample is more meaningful for reference than that in the whole process industry. Thus, the readiness indexes' positions of the four races and 25 domains of the target company in the fine chemical industry are illustrated in Figs. 10c and 10d, respectively. Additionally, the basic strategies for four ranges under the position of the evaluated aspect are designed: (1) 0%–25%, these aspects possess the industry leading level, and emphasis is put on the focus on the concrete issue in the business operation; (2) 25%–50%, these aspects have good foundation for intelligent manufacturing transformation (one critical capability that needs to be improved is to learn from the advanced experience of the same industry and rapidly guide their own activities); (3) 50%–75%, there is a certain gap between these aspects and the general level (however, they have a basic foundation of development and "second-mover" advantages); (4) 75%–100%, these aspects

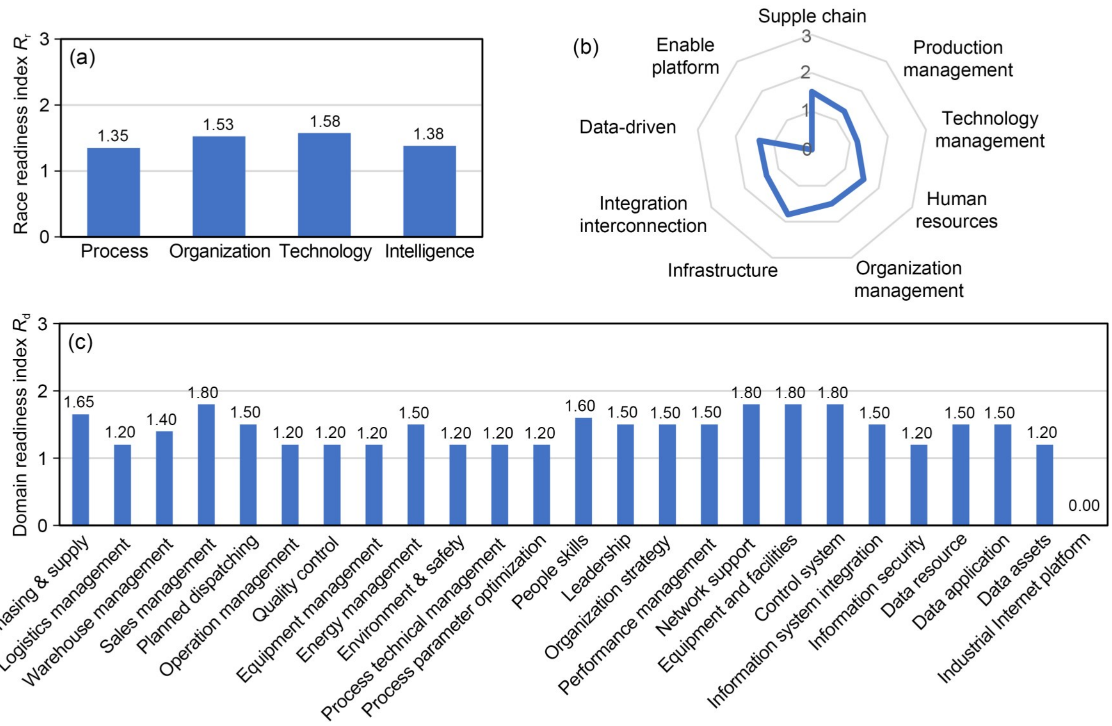

Fig. 9 The readiness index of the target company: (a) race index R_r; (b) species index R_s; (c) domain index R_d

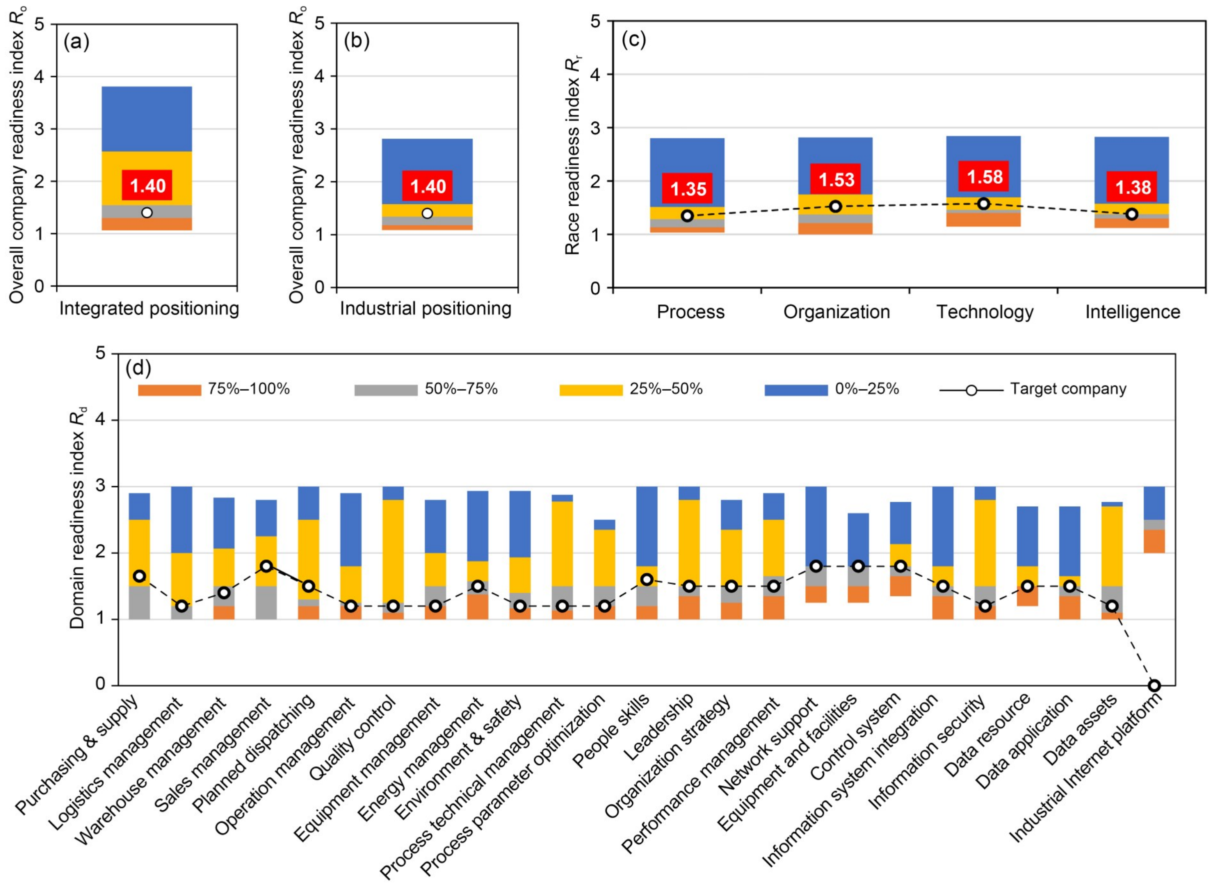

Fig. 10 Readiness index of the target company: (a) integrated positioning of R_o in 196 companies; industrial positioning of R_o (b), race index R_r (c) and domain index R_d (d) in 44 fine chemical industry companies

have huge room for improvement, and the main construction goal is to improve the basic foundation and rapidly copy the successful practices in ranges of (1) and (2). Importantly, as discussed before, a large amount of sample data is the basis of this analysis.

5 Conclusions

This work proposes a novel model that focuses on the process industry to measure the intelligent manufacturing readiness for companies. The PIMRI defines the detailed requirements of six readiness levels according to the maturity model of intelligent manufacturing capability (GB/T 39116-2020). The structure of PIMRI comprises three layers, in which the process, technology, organization, and intelligence are placed on the first layer, and they are the four major dimensions for evaluation. Nine species and 25 domains are further divided based on the top four dimensions. In addition, 249 characteristic items are formulated for each domain related to different readiness levels. Meanwhile, we designed an easy-to-use questionnaire to help industrial companies carry out self-diagnosis. To the best of our knowledge, the PIMRI is the first model that has been created specifically for the process industry, and it is the first model that includes intelligence as an independent dimension for intelligent manufacturing readiness evaluation. The intelligence dimension concentrates on the data governance and Internet platform, which are the essential components in the intelligent manufacturing transformation.

A real-world case for 196 process-industry companies is displayed to explain how to use the PIMRI, thereby verifying the usability of this newly proposed model. The PIMRI could not only give guidelines for the target company but also provide industry information or a tool to evaluate the readiness degree of intelligent manufacturing for the government, solution vendors, or some third-party consulting companies. The model could help industrial companies conduct intelligent manufacturing transformation considering both technical feasibility and economic feasibility. After self-diagnosis, the target company could choose the most suitable best practices as the reference in upper-level companies according to its current situation.

However, the PIMRI also has some limitations. First, this model could only find the short slabs in the industrial companies without giving the method to deal with them. Collecting successful cases in practice and summarizing the ripe experience are the two ways to illustrate the recommended transformation roadmap. In addition, some other domains that are not included in this model would be found due to the rapidly developing advanced technologies and many practical applications. These two aspects are also the key points of our future research and practice. Finally, we hope that the PIMRI will have a positive effect on the intelligent manufacturing transformation for process-industry companies.

Contributors

Lujun ZHAO and Yuqi QI designed the research. Jiaming SHAO and Yuqi QI processed the data. Jiaming SHAO and Lujun ZHAO drafted the paper. Jian CHU and Yiping FENG helped organize the paper. Jiaming SHAO, Lujun ZHAO, and Yiping FENG revised and finalized the paper.

Compliance with ethics guidelines

Lujun ZHAO, Jiaming SHAO, Yuqi QI, Jian CHU, and Yiping FENG declare that they have no conflict of interest.

Data availability

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

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