Enhancing strategy for Industry 4.0 implementation through maturity models and standard reference architectures alignment

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Abstract

Purpose – A maturity model for Industry 4.0 (I4.0 MM) with influencing factors is designed to address maturity issues in adopting Industry 4.0. Standardisation in I4.0 supports manufacturing industry transformation, forming reference architecture models (RAMs). This paper aligns key factors and maturity levels in I4.0 MMs with reputable I4.0 RAMs to enhance strategy for I4.0 transformation and implementation.
Design/methodology/approach – Three steps of alignment consist of the systematic literature review (SLR) method to study the current published high-quality I4.0 MMs, the taxonomy development of I4.0 influencing factors by adapting and implementing the categorisation of system theories and aligning I4.0 MMs with RAMs.
Findings – The study discovered that different I4.0 MMs lead to varied organisational interpretations. Challenges and insights arise when aligning I4.0 MMs with RAMs. Aligning MM levels with RAM stages is a crucial milestone in the journey toward I4.0 transformation. Evidence indicates that I4.0 MMs and RAMs often overlook the cultural domain.
Research limitations/implications – Findings contribute to the literature on aligning capabilities with implementation strategies while employing I4.0 MMs and RAMs. We use five RAMs (RAMI4.0, NIST-SME, IMSA, IVRA and IIRA), and as a common limitation in SLR, there could be a subjective bias in reading and selecting literature.
Practical implications – To fully leverage the capabilities of RAMs as part of the I4.0 implementation strategy, companies should initiate the process by undertaking a thorough needs assessment using I4.0 MMs.
Originality/value – The novelty of this paper lies in being the first to examine the alignment of I4.0 MMs with established RAMs. It offers valuable insights for improving I4.0 implementation strategies, especially for companies using both MMs and RAMs in their transformation efforts.

Keywords Industry 4.0, Maturity model, Standard, Reference architecture, Enhancement strategy
Paper type Research paper

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1. Introduction

Currently, many companies are required to meet the demand for faster delivery times, customised products with higher quality and more automated and efficient processes, as argued by Zheng *et al.* (2020), leading them to the fourth industrial revolution or Industry 4.0 (I4.0). There have been many research studies discussing the topic of I4.0. However, some researchers, such as Fatorachian and Kazemi (2018) and Kolberg *et al.* (2017), noted that they generally only focus on specific processes within the company, such as analysing enabling technologies. Therefore, this indicates the need to examine the impact of I4.0, which considers all processes, as mentioned by Piccarozzi *et al.* (2018) and Zheng *et al.* (2020). In addition, Angreani *et al.* (2020) noted several challenges in implementing I4.0 concepts, particularly at strategic levels. The I4.0 maturity model (MM) used to be a strategic guide to adopting I4.0 in companies, but it can also be used to address these problems.

Wagire *et al.* (2021) argued that evaluating a company's MM is a fascinating topic in the I4.0 research domain, as also mentioned by Kohlegger *et al.* (2009) and that a company's capabilities develop through different stages of maturation over time. Since there are continuous, significant changes in the strategic direction or the daily operation that led to the evolution of digital transformation, companies must understand the current state of their maturity. Some researchers, such as Voß and Pawlowski (2019) and Wagire *et al.*, (2021), concluded that MMs guide an organisation and its stakeholders through the maturation process more effectively and efficiently. Regarding MM in I4.0, some works in the literature mention MM in I4.0 in several ways, such as roadmap, framework and maturity index. Several works have focused on conducting critical and systematic literature reviews (SLRs) to analyse the multiple perspectives of MM. All of the reviewed works have one goal: to measure the current state of companies and prepare them to implement the I4.0 concept well in the future (Angreani *et al.*, 2020; Elibal and Özceylan, 2021; Mittal *et al.*, 2018; Şener *et al.*, 2018). However, those reviews only focus on particular industrial types, namely SME Mittal *et al.* (2018) and manufacturing and logistics Angreani *et al.* (2020).

In line with supporting the transformation of I4.0, Li *et al.* (2018) described that, to a certain degree, the standardisation of architecture is essential to I4.0 or smart manufacturing strategies worldwide. Some of these standards have now been integrated into the I4.0 reference architecture models (RAMs) (Li *et al.*, 2018; Nakagawa *et al.*, 2021; Takahashi *et al.*, 2017). A critical review has been conducted to study emerging RAMs (Moghaddam *et al.*, 2018) and revealed that service orientation relying on digitalisation and Internet of Things (IoT) integration is the essential characteristic of the architecture. Some researchers investigated the impact of the I4.0 introduction on the broader context of a company. For example, Kornyshova and Barrios (2020) studied the impacts of I4.0 on TOGAF 9.2, a framework for Enterprise Architecture (EA) and Nowakowski *et al.* (2018) identified the challenges in EA implementation to enable I4.0 transformation through expert interviews and proposed a systematic EA planning process specification and four-layered I4.0 meta-model.

The aspects of RAMs contain several capabilities of the company, for example, communication capability and integration capability in the logical aspect, as noted by Takahashi *et al.* (2017). Mittal *et al.* (2018) argued that the aspects in the RAMs provide companies with the technical and business requirements for implementing I4.0. Companies face significant challenges in implementing I4.0 due to the need for a holistic view of both business and technical requirements, as emphasised by Santos and Martinho (2020), and it is evident that RAMs offer a practical solution to bridge this gap and provide the necessary framework for a successful I4.0 adoption. Therefore, factors that indicate the maturity of companies for I4.0 contained in the MM should align with the aspects in the RAM. Thus, companies can use the requirements provided in RAMs as guidelines to improve their maturity in adopting I4.0.

Even though several references have discussed different perspectives related to I4.0, there is a lack of thorough consideration of the factors that affect the company's maturity in adopting I4.0 from a technical and managerial perspective. Likewise, there is no alignment analysis of these factors with the aspects of well-known I4.0 RAMs. Thus, this study seeks to fill this gap by performing an SLR of I4.0 MMs to identify the taxonomy of I4.0 maturity factors and levels and then aligning the result to the aspects and stages of current reputable I4.0 RAMs to enhance the strategy of I4.0 implementation. Thus, the main research questions addressed in this paper are:

RQ1. Do existing MMs align with current I4.0 RAMs?

RQ2. How can the alignment enhance the strategy for I4.0 implementation?

This paper consists of the following: Section 2 shows the methodology of the research; Section 3 reports the main results of SLR, the development of a new taxonomy for I4.0 MM and the structural level of maturity; Section 4 describes the current well-known I4.0 RAMs and the alignment of I4.0 MMs to RAMs; Section 5 discusses our findings, followed by recommendations and outlining the agenda of future research and last but not least, section 6 contains conclusions and limitations.

2. Methodology

There are three main steps carried out in this study: SLR, taxonomy development and the alignment method. Figure 1 illustrates the overall steps of the methodology.

2.1 Systematic literature review

This study uses the SLR method as an approach to analyse the literature related to the I4.0 MMs. A review protocol was used as the SLR methodology. Figure 2 depicts the review protocol used in the SLR and includes the search and selection phases utilised in this research.

In the beginning, to frame the SLR research questions (SLR-RQs), this research develops PICOC (Population, Intervention, Comparison, Outcome and Context) (Kitchenham and Charters, 2007), which consists of (1) Population: Industry 4.0, smart manufacturing and smart factory; (2) Intervention: maturity model; (3) Comparison: N/A; (4) Outcomes: reliability of influencing factors of I4.0 in existing maturity models and (5) Context: research in academia and industry. Based on PICOC, the SLR research questions are:

SLR RQ1. What dimensions do researchers use to develop Industry 4.0 maturity models?

SLR RQ2. What are the most used and influencing parameters in those dimensions?

The answer to these SLR research questions will be used as input in taxonomy development to answer this study's main research questions.

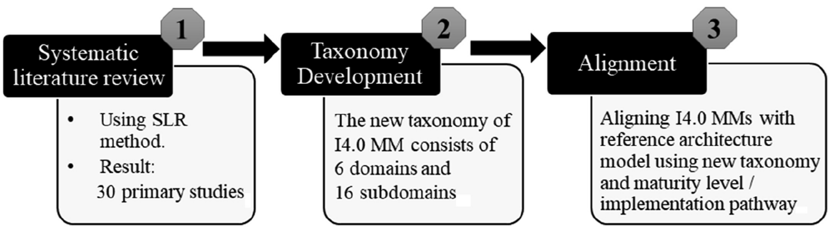

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Figure 1. Overall research methodology

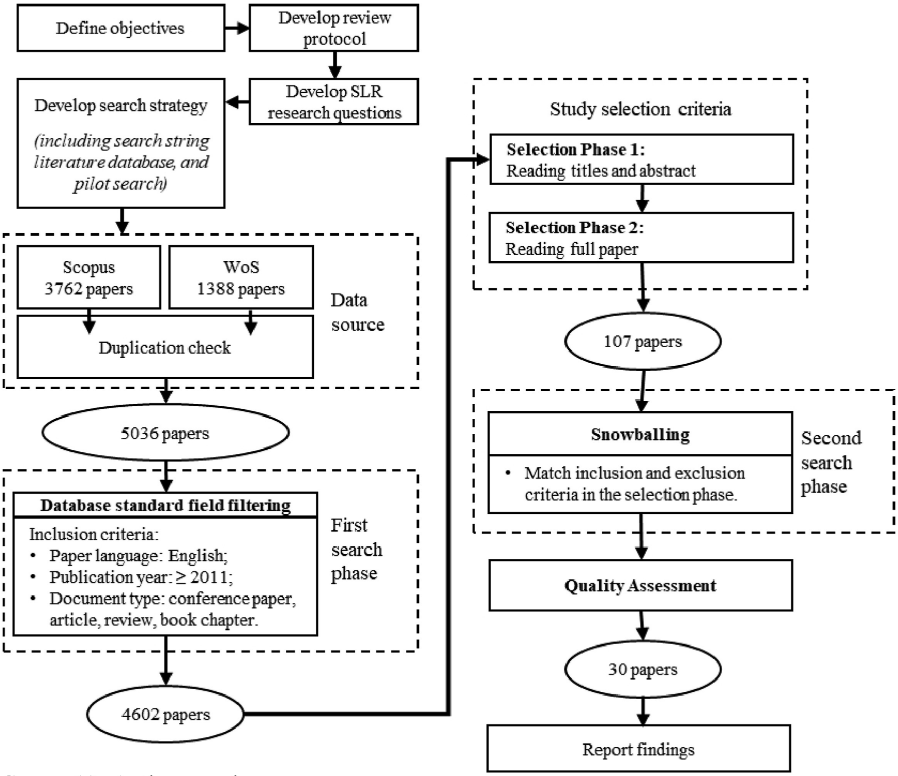

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Figure 2.
SLR protocol and search process result

Next, this study defines a search strategy to find relevant literature effectively: searching keywords and strings, searching and collecting articles and implementing quality assessment (QA). The research constructs a structural search string containing keywords to test the rigour of the search process and uses the Scopus and Web of Science (WoS) databases as our source of literature. During the test, we found that we must include the word "industrie 4.0" because several works of literature use this German terminology, although the articles are in English. Zheng *et al.* (2020) argued that the adoption of advanced technologies in manufacturing, including Industry 4.0, smart manufacturing and smart factory, has been a topic of debate. This study confirmed these findings during our search process, where articles related to our focus often mentioned "smart factory" and "smart manufacturing". The search string testing also indicated the need to include other terms, such as "maturity model", "assessment" and "readiness model". The final search string, constructed after multiple tests, is as follows:

(industry 4.0"OR" industrie 4.0"OR" smart manufactur"OR" smart factory)

AND (maturity OR readiness OR assessment OR framework)

The first search process using the search query string from Scopus resulted in a collection of 3,762 pieces of literature and 1,388 references from WoS. The search process was carried out in the literature title, abstract and keywords sections.

The search string is a basic string that must be adjusted with specific filtering criteria. This study has searched using the search string by title, abstract and authors' keywords, with the year publication being between 2011 and 2021 – the types of publications are journal articles, book chapters and conference papers published in English. Filters are applied to the most relevant literature subject areas related to this study's research questions.

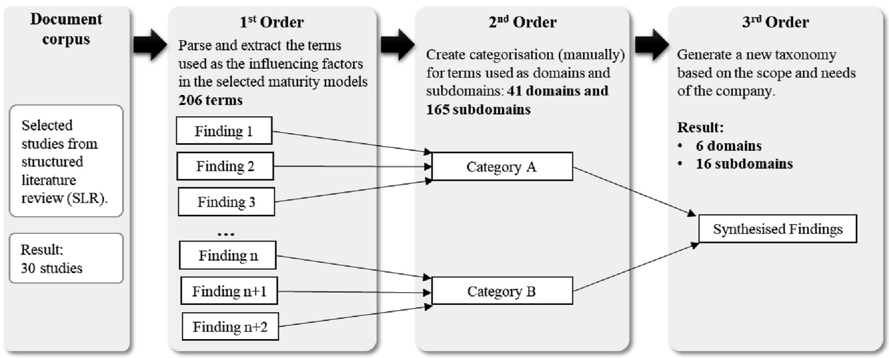
The first selection phase involved investigating the papers' titles and abstracts, excluding them from the research scope to achieve the research objectives. The second selection phase was done by investigating the entire paper. In addition to all the criteria mentioned above, articles that only focus on discussing the implementation of the existing maturity model are also discarded. The results of the second selection phase were 107 papers. The second search involved a snowballing strategy (Dekkers *et al.*, 2022) from the reference list of the selected studies. This phase obtained 15 other relevant articles, thus resulting in a total of 122 studies.

Next, we implemented the quality assessment process based on four main topics of questions with the same weight. As adopted from Angreani *et al.* (2020), Kitchenham and Charters (2007) and Wen *et al.* (2012), each topic consists of some questions to assess the rigorousness, credibility and relevance of selected studies. Each question has only three optional answers: "yes" (scored as "1"), "partly" (scored as "0.5") and "no" (scored as "0"). These topics are: [1] research aims, method and theoretical foundation; [2] structure accuracy, scope of dimensions; [3] structure accuracy, maturity levelling model and [4] practice orientation.

Two researchers performed the literature review's quality assessment individually and discussed each other's results. They discussed disagreements before the results were agreed upon. To ensure the reliability of selected studies, we only included literature with a QA score of more than 5 on a scale of 10 for the following analysis. The study managed the selected articles using Mendeley software (www.mendeley.com), and the papers were catalogued there. After completing the first reading, the article was tagged according to the domain of the MM. In addition, we highlighted the sections of the papers that have potential aspects related to the domain of I4.0. Then, we managed all of them using a spreadsheet.

2.2 Taxonomy development

The existing scientific literature presents a variety of MMs outlining the typical standard domains in companies, such as Hizam-Hanafiah *et al.* (2020) and Schumacher *et al.* (2016). The domains are often used to refer to areas that have the potential to achieve the I4.0 vision (Lichtblau *et al.*, 2015). Some literature also refers to these domains as components of business processes associated with achieving I4.0 goals. This study creates a new taxonomy of these domains with the steps shown in Figure 3 by adapting and



Source(s): Authors work adapted from Dekkers (2017)

Figure 3. Steps of new taxonomy development of MM for Industry 4.0

implementing the categorisation of system theories, such as in the application of system theories from Dekkers (2017) and post-processing steps of the smart literature review framework in Asmussen and Møller (2019).

2.3 Alignment method

Alignment aims to discover that this study's new taxonomy, which contains the factors that affect the I4.0 MMs, aligns with the current well-known I4.0 RAMs. Figure 4 depicts the alignment process, which consists of three steps. In the first step, we explored several I4.0 RAMs. Next, we extracted information from the search results and manually compared the terms and scope used in the models. As the final step of the alignment, we mapped all the domains and subdomains of the new taxonomy we have created to the extracted information from these RAMs.

3. Review of MMs for industry 4.0

3.1 Basic data analysis

Through the SLR protocol, the research identified 30 studies in the area of I4.0 MMs (Table 1). The distribution of papers over the years shows the change of interest in the maturity model related to I4.0, as depicted in Figure 5. Among the 30 selected studies, 11 articles were published in reputable journals, five papers were published as conference contributions and two references appeared in book chapters. We discovered 12 (40%) studies published individually by industrial practitioners, enterprise consultants, consortiums of academics and industries or government institutions. Figure 6 shows the publication type distribution of selected studies.

3.2 Structural domain and related analytical categories

We found 206 different terms used in current MMs using Table 1 and Figure 3, which answer SLR RQ1. Furthermore, the newly developed taxonomy also addresses SLR RQ2. The new taxonomy consists of six domains and 16 subdomains (Table 2). We made six components as level 1 (domain) because these components are the company's operational needs (Li *et al.*, 2018; Martínez-Olvera and Mora-Vargas, 2019; Schumacher *et al.*, 2016; Da Silva *et al.*, 2020; Wagire *et al.*, 2021; Zheng *et al.*, 2020). Due to the constraint of paper length, we put the description of those domains and subdomains in the supplement file.

3.3 Structural level of maturity in I4.0 MMs

By using the selected primary study, as shown in Table 1, organisations can typically adopt four to six levels of I4.0 MMs, with each level representing a higher degree of integration and

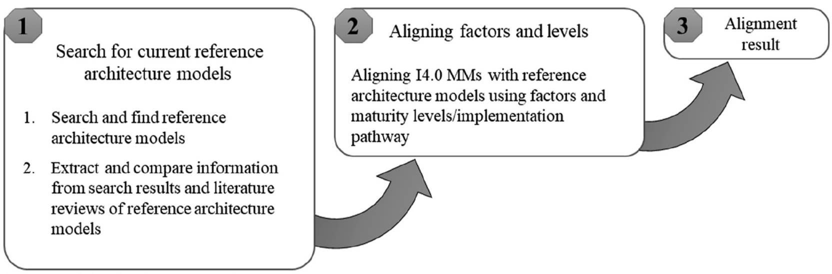


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Figure 4.
Steps of alignment to I4.0 reference architecture models

Table 1. Selected studies of I4.0 MMs

MM no.	Metric Reference	Assess domain	Subdomain	Level of maturity	MM development methods: Literature review	Survey	Workshop	Conceptual modelling	QA-score
MM-01	Bechthold and Lauenstein (2014)	4	9	7		X		X	6.25
MM-02	Rockwell Automation (2014)	4	–	5			X		5.42
MM-03	Lichtblau *et al.* (2015)	6	18	6		X	X	X	8.13
MM-04	Geissbauer *et al.* (2016)	6	–	4		X		X	5.42
MM-05	Schumacher *et al.* (2016)	9	6	5	X			X	7.50
MM-06	VDMA Industrie 4.0 Forum (2016)	12	2	5	X			X	7.50
MM-07	Bauer *et al.* (2016)	8	26	–		X		X	6.88
MM-08	Agca *et al.* (2017)	6	37	4		X		X	6.46
MM-09	EDB (2017)	16	–	6	X	X	X	X	6.67
MM-10	German Innovation Centre for Industry 4.0 (2018)	4	21	10	X	X	X	X	5.42
MM-11	MITI (2018)	21	–	5	X			X	7.08
MM-12	Colli *et al.* (2019)	5	–	6	X	X	X	X	7.71
MM-13	MOI (2018)	5	17	5	X			X	7.29
MM-14	Sony and Naik (2019)	6	17	–	X			X	5.63
MM-15	Calabrese *et al.* (2020)	9	21	–		X		X	7.92
MM-16	Garzoni *et al.* (2020)	–	–	4	X			X	6.25
MM-17	Santos and Martinho (2020)	5	–	6	X	X	X	X	8.54
MM-18	Schuh *et al.* (2020)	4	8	6	X			X	8.13
MM-19	Tripathi and Gupta (2021)	7	17	2	X			X	8.54
MM-20	Wagire *et al.* (2021)	7	38	24		X		X	7.71
MM-21	Gökalp *et al.* (2019)	5	–	5	X			X	5.83
MM-22	Leyh *et al.* (2016)	4	–	5	X				6.67
MM-23	Akdil *et al.* (2018)	3	3	4	X	X		X	7.50
MM-24	Scremin *et al.* (2018)	3	–	5	X	X		X	8.33
MM-25	Jung *et al.* (2016)	4	–	6				X	6.88
MM-26	Ganzarain and Errasti (2016)	3	–	5		X		X	6.04
MM-27	Lee *et al.* (2017)	4	10	3				X	7.71
MM-28	Fantini *et al.* (2020)	6	–	3 to 7	X	X		X	6.88
MM-29	Frank *et al.* (2019)	5	–	3 to 4	X			X	5.83
MM-30	De Carolis *et al.* (2017)	5	–	5				X	7.08

Source(s): Authors' work

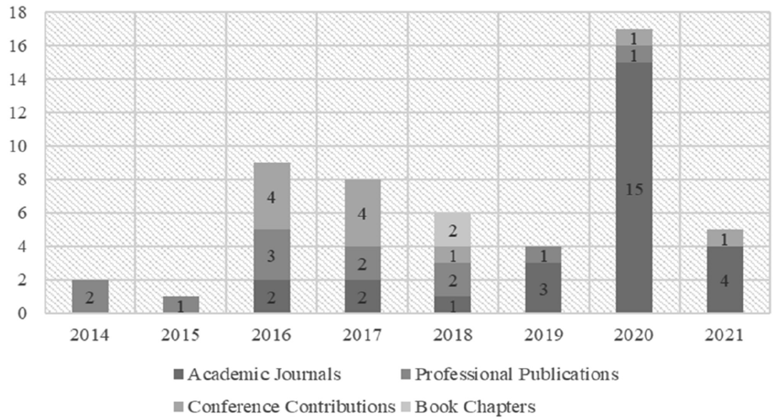

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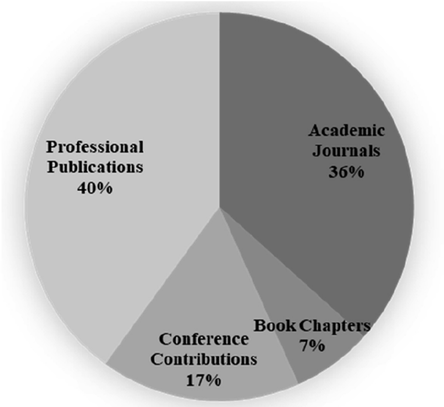
Figure 5. The distribution publications of selected studies per year



Source(s): Authors work

Figure 6. Primary studies publication type

optimisation of I4.0 technologies and practices. Although some of those selected references did not mention it, the levelling of maturity in those MMs can be considered a pathway of implementation. While the exact number of levels may vary depending on the specific maturity model, having four to six levels is generally reasonable for most organisations to adopt. By using the same method in taxonomy development (Figure 3), we grouped levels into five key levels that start with level 0 or stage 0, as a foundation level. At the same time, it includes the highest level of industrial revolution three, such as digitisation and IT connectivity. Figure 7 depicts that each level represents distinct progress in an organisation's journey towards I4.0 adoption. It allows for a structured approach as a pathway for I4.0 implementation, providing a clear roadmap for organisations to follow as they progress towards more advanced maturity levels. The description of each level is as follows:

3.3.1 Level 0 – foundation. At this initial level, organisations lay the groundwork for adopting I4.0. It involves building the fundamental infrastructure for digitalisation, focusing on elements such as connectivity and data collection and establishing a basic framework for

Domain	Subdomain	MM-1	MM-2	MM-3	MM-4	MM-5	MM-6	MM-7	MM-8	MM-9	MM-10	MM-11	MM-12	MM-13	MM-14	MM-15	MM-16	MM-17	MM-18	MM-19	MM-20	MM-21	MM-22	MM-23	MM-24	MM-25	MM-26	MM-27	MM-28	MM-29	MM-30
Technology	Advance IT	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X
	Data-and information	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X		X	X	X	X		X	X
Product	ICT add-on functionalities	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X			X
	Data analytics in usage phase	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X		X	X	X		X	X			
Operation/ Process	Integration		X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X			X
	Inventory and SC	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X		X			
	Quality	X	X	X	X			X	X	X		X		X	X	X		X	X	X	X	X	X		X			X			X
Resource	Asset utilisation	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X					X	X			
	Employee	X	X	X	X	X		X	X	X	X	X	X	X	X	X		X	X	X	X			X	X		X	X	X		
Culture	Collaboration	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X			X					X
	Willingness to change	X		X		X			X		X			X	X	X	X	X	X	X	X										
Organisation governance	Digital leadership capability	X	X			X		X	X	X	X	X		X		X			X		X			X				X			
	Innovation management	X	X	X	X		X	X	X	X	X			X	X			X	X	X		X		X							
	Agility	X				X		X		X	X				X	X			X	X	X							X			
	Investment for I4.0		X	X				X	X					X	X			X		X	X			X	X			X			X
	Strategy for I4.0	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X			X

Source(s): Authors' work

Table 2. Detail domains and subdomains included in maturity models

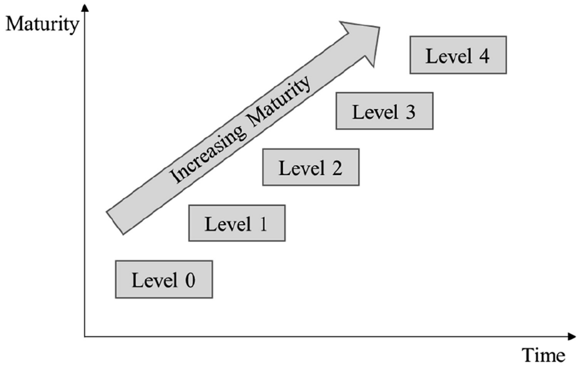


Figure 7. Five key levels as a pathway of I4.0 implementation

Source(s): Authors work

I4.0 technologies. The primary goal is to create a foundation to support more advanced stages of digital transformation.

3.3.2 Level 1 – integration. At level 1, the emphasis shifts to integrating assets, data and systems. This level marks the beginning of leveraging integrated data for enhanced visibility and control within an organisation's operations. It transforms towards a more connected environment, setting the stage for more comprehensive data-driven insights.

3.3.3 Level 2 – data-driven insights. At level 2, organisations make progress in leveraging integrated data to gain insights and make decisions. Data analysis is taking centre stage, enabling organisations to gain insights from the data collected. This level empowers data-driven decisions and optimisation in various processes, thereby increasing efficiency and performance.

3.3.4 Level 3 – advanced automation. At level 3, the focus shifts to advanced automation and control. Organisations introduce adaptive systems, advanced robotics and autonomous processes, reducing the reliance on human intervention in manufacturing and operations. This level marks a significant step towards achieving higher automation and operational excellence.

3.3.5 Level 4 – smart services and autonomy. Level 4 represents the top of I4.0 maturity, emphasising full autonomy and self-optimisation. Systems and processes are operated with minimum human intervention, utilising advanced AI and machine learning algorithms to make real-time decisions. Data-driven insights are leveraged for predictive maintenance, resource allocation and continuous improvement, reinforcing an organisation's competitive advantage and adaptability.

4. Aligning I4.0 MMs with reference architecture models

4.1 Reference architecture models

Several terms are used concerning I4.0, such as smart manufacturing or industrial internet (Li *et al.*, 2018). However, based on the study results of Li *et al.* (2018) and Takahashi *et al.* (2017), in this paper, all these terms can be concluded into one topic: Industry 4.0. In other words, Industry 4.0 can be defined as a combination of industrialisation and informatisation that needs systematic solutions, methodologies and standardisation.

Standardisation in I4.0 is essential to support the transformation of the manufacturing industry. Standards are vital for realising the I4.0 vision when different stakeholders and enterprises interact interoperably (Grángel-Gonzalez *et al.*, 2017). Several standards have been developed by standard development organisations or SDOs (Hasegawa, 2017; Li *et al.*, 2018). Industrial organisations, working groups or technical committees have actively developed some standards for smart manufacturing (Kannan *et al.*, 2017; Li *et al.*, 2018). Furthermore, some countries have also published their own standards, landscapes and roadmaps due to the different stages of smart manufacturing development (Li *et al.*, 2018). Although all of those standards have different stages in smart manufacturing development, they share the same following principles: [1] respect for other standardisation activities, [2] focus on system integration and [3] discover and take action on standardisation blank areas (Li *et al.*, 2018; Plattform Industrie 4.0; JMFRRI; SCI40, 2017).

Several Industry 4.0-related RAMs have been regulated as standards in several countries. Domestic companies are encouraged to comply with the models. Furthermore, to implement systematic standardisation and develop a solution for I4.0, some smart manufacturing standards developed by different industrial organisations and SDOs are integrated into RAMs (Li *et al.*, 2018; Nakagawa *et al.*, 2021). The reference architectures for I4.0 document the architecture elements collected from systems in the I4.0 domain. The architecture elements describe a complex system's top-level structure and internal relationships (Li *et al.*, 2018; Nakagawa *et al.*, 2021). Reference architectures provide knowledge on developing and standardising systems and facilitating the integration of complex systems with diversified components using international standards (Megow, 2020; Takahashi *et al.*, 2017).

Some studies have conducted a structured review and survey on RAMs. We include five main RAMs discussed in several literature reviews related to them, while many other models are variations of them (Nakagawa *et al.*, 2021). The five models of reference architecture are as follows:

(1) Reference architecture model Industrie 4.0 (RAMI 4.0) (Adolphs *et al.*, 2015)

- RAMI4.0 is well-suited for complex manufacturing industries or manufacturing environments that require a highly integrated and standardised approach, as described in Weber *et al.* (2017).
- It is applicable to all industry sectors and suitable for both discrete manufacturing and process industries, while it can also be employed to attain a comprehensive integration of automation, business information and manufacturing execution functions (Lydon, 2019).

(2) Smart manufacturing ecosystem (NIST-SME) (Lu *et al.*, 2016)

- The NIST-SME architecture mainly focuses on ICT application systems like CAD, CAM and SCM, as mentioned in Li *et al.* (2018), making it challenging to recognise the significant role of industrial technology in smart manufacturing, including 3D printing, intelligent robots and new materials.
- NIST-SME is suitable for small and medium-sized enterprises embarking on their Industry 4.0 journey, and it works effectively in scenarios where budget constraints are a consideration, offering a more practical and cost-effective approach (Lu *et al.*, 2016).

(3) Industrial internet reference architecture (IIRA) (Lin *et al.*, 2022)

- IIRA is well-suited for organisations that require a flexible framework to adapt to different contexts and ecosystems, such as those reported in Weber *et al.* (2017), while it is versatile and can work effectively across various industries, providing a standardised approach to Industry 4.0 adoption (Weber *et al.*, 2017).

- In IIRA, the extensive range leads to comprehensive coverage of subjects, while specific instructions for implementation are only partially included (Bader *et al.*, 2019).

(4) National intelligent manufacturing standards architecture (IMSA) (MIIT; SAC, 2021)

- IMSA is valuable for data-intensive industries focusing on advanced data analytics and automation (Li *et al.*, 2018). Similar to RAMI 4.0, IMSA focuses on manufacturing industries, but it includes the product marketing phase (Sino-German Industrie 4.0, 2018).
- It can help manufacturers improve their operations, reduce costs and enhance operational efficiency (MIIT; SAC, 2021).

(5) Industrial value chain reference architecture (IVRA) (Industrial Value Chain Initiative, 2018)

- IVRA is a high-level architecture that offers the flexibility to embrace various technologies, platforms and tools, as those mentioned in Li *et al.* (2018) and Nakagawa *et al.* (2021).
- It optimises the entire value chain by aligning strategies and standards among partners, where the essential scenarios are supply chain integration, data collaboration and seamless communication between value chain participants.

Several literature reviews that discuss those five RAMs are Takahashi *et al.* (2017), Li *et al.* (2018) and Megow (2020). Han (2020) only discusses four of them and omits IIRA in his review. Only RAMI 4.0 and IIRA are discussed in the literature reviews conducted by Weyrich and Ebert (2016), Weber *et al.* (2017) and Unal (2019), while Bader *et al.*, (2019), Li *et al.* (2018), and Nakagawa *et al.* (2021) added a discussion of IVRA to their papers.

4.2 Aligning key drivers of I4.0 MMs to reference architecture models for I4.0

I4.0 aims to bring new core capabilities and competencies that combine information, industrial, and management technologies. The development of those three types of technologies, or their domains, can properly position the components of I4.0 with standardisation (Li *et al.*, 2018). Hence, the development of company maturity for I4.0 has to comply with the reference architecture models of I4.0 and its standardisation. Moreover, MMs are needed to help organisations prepare for I4.0.

From the RAMs mentioned in section 4.1 above, several researchers have analysed aspects involved within these models and aggregated them (Table 3). Takahashi *et al.* (2017) examined those RAMs and determined four aspects with description capabilities for each. By using a different semantics approach and analysis, Li *et al.* (2018) and Helmann *et al.* (2020) concluded that four aspects can be aggregated into RAMs, consisting of three main aspects related to the technological revolution and one additional aspect of human or organisation promotion. Our research utilised these aspects to align the new taxonomy of I4.0 MMs with RAMs.

Based on the method in Figure 4, we have mapped the literature involving all factors of our taxonomy. To be able to map the taxonomy to RAMs, we first mapped the taxonomy to aspects of RAMs based on research results from Takahashi *et al.* (2017), Li *et al.* (2018) and Helmann *et al.* (2020). This mapping identifies the alignment between the factors in the taxonomy and aspects of the RAMs. The mapping results are shown in Table 4.

As shown in Table 4, the factors most closely aligned with aspects of the RAMs are integration (operation/process domain) and advanced IT (technology domain). Almost all

Table 3. Mapping factors of the new taxonomy to I4.0 reference architecture models

Aspects of reference architecture models	
Based on (Takahashi *et al.*, 2017)	Based on (Li *et al.*, 2018; Helmann *et al.*, 2020)
• Logical (L)consists of the following – Usage (L1) – Business (L2) – Information (L3) – Communication (L4) – Integration (L5) – Asset (L6) – System model representation (L7) • Physical (P)consists of the following – Interaction among enterprises (P1) – Production system hierarchy (P2) – Product (P3) • Lifecycle (LC) consists of the following – Meta-lifecycle (LC1) – Product lifecycle (LC2) – Supply chain/Value chain (LC3) – Service lifecycle (LC4) • Comprehensive (C)consists of the following – Security/Safety/Privacy (C1) – Regulation (C2)	• Business /Management (domains and technology revolution) (B)consists of the following – System hierarchy (B1) – Product lifecycle (B2) – Business (supply chain) lifecycle (B3) – Production lifecycle (B4) – Manufacturing mode development (B5) • Industrial technology revolution (I) consists of the following – New equipment (I1) – New manufacturing process techniques (I2) – New energy (I3) – New materials (I4) • Information technology revolution (IT) consists of the following – Function layers (IT1) – Communication technology development (IT2) – Network technique development (IT3) – Data storage technology development (IT4) – Database technology development (IT5) – IT infrastructure development (IT6) – CAX /Simulation technology development (IT7) • Human /Organisation promotion (HO) consists of the following – Organisation management scope (HO1) – Human resource talent levels (HO2) – Capability /Performance (HO3)

Source(s): Authors' work

factors in the new taxonomy have one to three relations with aspects in the RAMs. However, one factor in the culture domain does not relate to any aspect, namely the willingness to change. Based on the mapping results in Table 4, we can finish the final mapping of our taxonomy to current reputable RAMs.

The final mapping results are shown in Table 5. Our research found that not all of the aggregate domains and subdomains of the selected MMs in our study can be mapped into aggregate aspects of I4.0 RAMs. Table 5 shows that RAMI4.0 is the most compatible with our new taxonomy of the five RAMs. The three-dimensional model of RAMI4.0 establishes three standards: situation analysis, requirements analysis and application model analysis (Li *et al.*, 2018). These three standards have covered almost all the factors in the taxonomy of I4.0 MMs. However, there are three factors not described by RAMI4.0, which are the least discussed factors among the five RAMs in Table 5.

The infrequently discussed factors among the five RAMs are "willingness to change, digital leadership capability and agility". These factors are closer to the non-physical or non-technological area and justify the fact that RAMs focus on technological and physical factors (Kagermann *et al.*, 2016). Meanwhile, the factor of agility, which means the ability to react quickly in changing markets and create more benefits, is only discussed explicitly in the NIST-SME model developed by NIST (Li *et al.*, 2018).

4.3 Aligning I4.0 MMs levels to the stages of reference architecture models for I4.0

The alignment of I4.0 MMs levels with the stages of RAMs represents a pivotal step in the journey towards digital transformation. I4.0 MMs provide a structured roadmap for

Table 4. Mapping factors of the new MMs taxonomy to aspects of I4.0 reference architecture models

Domain	Subdomain	L1	L2	L3	L4	L5	L6	L7	P1	P2	P3	LC1	LC2	LC3	LC4	C1	C2	B1	B2	B3	B4	B5	I1	I2	I3	I4	IT1	IT2	IT3	IT4	IT5	IT6	IT7	HO1	HO2	HO3
Technology	Advance IT							X																				X	X	X	X	X	X			
	Data-and information			X													X														X					
Product	ICT add-on functionalities										X																									
	Data analytics in usage phase	X									X																									
Operation/Process	Integration					X				X		X	X					X	X			X					X									
	Inventory and supply chain													X						X																
	Quality														X																					
Resource	Asset utilisation						X																													
	Employee																																		X	X
Culture	Collaboration				X				X																											
	Willingness to change																																			
Organisation governance	Digital leadership capability		X																															X		X
	Innovation management																							X	X	X										
	Agility																																			X
	Investment for I4.0																						X													
	Strategy for I4.0																	X																X		

Source(s): Authors' work

Domain	Subdomain	RAMI4.0	NIST-SME	IMSA	IIRA	IVRA
Technology	Advanced IT	X	X	X	X	X
	Data-and information	X	X	X	X	
Product	ICT functionalities on products	X	X	X	X	
	Data analytics feature on products	X	X	X	X	
Operation/process	Integration	X	X	X	X	X
	Inventory and supply chain	X	X	X	X	X
	Quality	X	X	X	X	X
Resource	Asset utilisation	X	X		X	X
	Employee	X	X			X
Culture	Collaboration	X		X	X	
	willingness to change					
Organisation governance	Digital leadership capability					X
	Innovation management	X	X			X
	Agility		X			
	Investment for I4.0	X		X		X
	Strategy for I4.0	X	X	X	X	X

Source(s): Authors' work

Table 5. Mapping factors of the new taxonomy to I4.0 reference architecture models

organisations to assess and advance their digital capabilities, categorising their progress into stages from foundational digitalisation to full autonomy. On the other hand, reference architecture models such as RAMI4.0, NIST-SME, IIRA, IMSA and IVRA offer a structured architectural framework to guide the implementation of I4.0 technologies and standards.

The alignment establishes a bridge between the progressive maturity of an organisation's digital capabilities, as outlined in I4.0 MMs, and the architectural framework provided, such as RAMI4.0, NIST-SME, IIRA, IMSA and IVRA. It facilitates an integration of evolving technological capabilities with the structural framework necessary for I4.0 adoption. Table 6 shows that for each level of I4.0 MMs, as described in section 3.3, specific capabilities and integration requirements correlate with the corresponding stages within the RAMs. Although not all levels of MMs can be precisely correlated, this alignment streamlines the implementation process. It enables organisations to make informed decisions regarding selecting and deploying technologies in harmony with the broader I4.0 ecosystem. However, NIST-SME and IVRA cannot be correlated at any particular level of I4.0 MM, as they do not provide an architecture that can be used as a path to implement I4.0 at higher levels.

5. Discussions, implications and perspectives for future research

5.1 Findings and proposed future directions

Based on the evidence, we noted some findings from the study that provide insight that can be used to enhance strategy for the successful implementation of I4.0 within companies:

(1) There are diversities of I4.0 MMs, which leads to different interpretations and understandings among companies.

The literature review revealed a diverse range of I4.0 MMs (Table 1 and Table 2), each offering unique perspectives on companies' maturity assessment. These models vary in terms of scope, focus and components. Despite there being 30 papers that address all domains in our new taxonomy of I4.0 MM, only a limited number of them represent all factors inside their domains.

Table 6. Aligning I4.0 MMs levels to the stages of reference architecture models for I4.0

	Standard reference architecture model				
I4.0 MMs Level/ Stage	RAMI4.0 from RAMI4.0 layers perspective (Adolphs *et al.*, 2015)	NIST-SME (Lu *et al.*, 2016)	IMSA from the perspective of IMSA intelligent features (MIIT; SAC, 2021)	IIRA from the perspective of IIRA crosscutting functions (Lin *et al.*, 2022)	IVRA (Industrial Value Chain Initiative, 2018)
Level 0 /Stage 0	Focuses on the foundational aspects of asset integration and connectivity	• NIST-SME provides an ecosystem consisting of applications of methods and tools (CAD, CAM, PLM, etc.) in different stages of product development, production and supply chain • NIST-SME does not provide an architecture that can be used as a pathway to a higher degree of I4.0 implementation	Focuses on basic connectivity and data collection at the foundational level	Focuses on connectivity to complete functionality at the system level	• IVRA consists of three independent layers based on different perspectives, including: business, activity and specification layers • As those layers are considered to supplement one another, IVRA does not provide an architecture that can be used as a pathway of I4.0 implementation
Level 1 /Stage 1	Asset and information integration • Advances asset integration and initial technology adoption • Enhances information integration		Interconnection • Advances the integration of assets and focuses on connectivity	Distributed data management • Management of distributed data through data interoperability (syntax and semantic interoperability)	
Level 2 /Stage 2	Functional and business integration • Advances in functional integration, focusing on automation and control systems • Shifts the focus to service integration and autonomy, including coordination of services within the functional integration		Fusion and sharing for big data • Utilizes data analytics for improved decision-making • Includes emerging business pattern	Industrial analytics • Implements data analytics for deriving insights • Develops adaptive systems in response to data-driven insights	
Level 3 /Stage 3			System integration for intelligent manufacturing and Emerging business pattern.	Intelligent and resilience control	
Level 4 /Stage 4			• System integration for intelligent manufacturing systems • Achieves smart manufacturing with advanced analytics and data-driven decision-making, e.g. diagnosis, prediction and decision-making, supporting the virtual-real iterative optimization based on data	• Establishes an intelligent ecosystem with self-optimizing, autonomous systems	

Source(s): Authors' work

Furthermore, according to Table 1, I4.0 MMs typically have four to six levels they can aim for. These levels show how well a company integrates and optimises I4.0 technologies and practices. While the exact number of levels can vary, having five levels is generally a good approach for most organisations (Figure 7). It gives a clear plan for implementing Industry 4.0 and guides them towards advanced maturity stages. However, what's required at each level is more important than the number of levels. The specific criteria and capabilities needed at each stage are crucial. They determine whether a company can fully benefit from I4.0 implementation.

Since I4.0 connects the global world with independent time and space, global involvement is required. A digital ecosystem is a new form of cooperation and collaboration in I4.0 (Kagermann *et al.*, 2016). However, the diverse I4.0 MMs, each characterised by its own distinct factors and levels, have given rise to varying perspectives and interpretations of an organisation's I4.0 maturity among other organisations. Consequently, this diversity hinders the realisation of effective collaborations among these organisations, posing a significant challenge.

Proposed research directions: the need for standardised semantics and weights of MM factors to allow diversity in prioritising the factors.

Companies worldwide need to have the same understanding of factors, domains and levels of I4.0 MM to improve their collaborations. Thus, it raises the need for standardised semantics comprising terminologies and structures representing domains, factors and metrics for I4.0 MMs to minimise misinterpretation and misunderstanding. This standardised semantic framework serves a dual purpose: it minimises the risk of miscommunication and facilitates the benchmarking of maturity assessment results, even when assessments employ different I4.0 MMs. Therefore, companies can select MMs that align with their specific industry, size and objectives while keeping the possibility of benchmarking. Customisation of MMs may be necessary to ensure relevance to the company's unique context.

This study provides the primary taxonomy for all industrial sectors, divided into levels 1 and 2 as domains and subdomains. However, for each sector, the taxonomy factors must be extended. For example, a building equipped with sensors could be an extension of the product domain in the construction sector. Another example is the healthcare sector; human health sensors embedded in the smartwatch are an extension of the product domain. We can also add telemedicine as an extension factor of the process/operations domain in the healthcare sector.

(2) I4.0 MMs and reference architecture model alignment: challenges and insights.

As shown in Table 4 and Table 5 while aligning between I4.0 MM and RAMs can be helpful, it is important to note that not all factors in I4.0 MM can be seamlessly mapped to aspects in the RAMs. It means no reference architecture examined in this study can be directly employed by companies seeking to enhance their maturity in implementing I4.0 based on the studied I4.0 MMs. This discrepancy may be attributed to the unique considerations given to various factors within the domains of the current MMs. For example, the NIST does not explicitly incorporate the culture domain within the NIST-SME model. However, NIST acknowledges innovation as part of the quality capability of the smart manufacturing system's (SMS) key capabilities (Lu *et al.*, 2016),which are mapped to the "organisation governance" domain. While innovation is a product of multiple cultural values, like a willingness to embrace change, it underscores the complexity and interplay of domains within the I4.0 MMs. This means, for example, that if a small–medium manufacturing company wants to adopt the NIST-SME model to improve their I4.0 maturity, an additional framework to promote willingness to change and collaboration is required.

Furthermore, as shown in Table 6, although not all levels of MMs can be precisely correlated with the corresponding stages in the RAMs, the alignment streamlines the implementation process and can help to avoid pitfalls that might happen in implementing a specific RAM to improve the I4.0 adoption level. For instance, when breaking down each process in RAMI4.0 into types and instances within the life cycle and value stream during implementation, Frysak *et al.* (2018) encountered a challenge in determining the appropriate layer for these processes.

Recommendations and proposed research directions: comprehensive assessments of companies' contexts and holistic view of MMs factors and domains.

As our research confirms that not all factors in maturity models for I4.0 are used in the reference architecture models, we recommend that to harness the full potential of reference architectures and I4.0 MMs, companies should initiate the process by conducting a comprehensive needs assessment. This assessment encompasses a detailed examination of their particular requirements, goals and limitations.

Further research also needs to be conducted to analyse all domains with a more profound approach that includes interactions between MM factors. For this purpose, we continue our research to study the factors comprehensively and explicitly develop relations between the factors in different domains. For example, the cultural-related subdomains must be related to quality in operations and innovation management domains. This integrated approach aims to provide a holistic understanding of the interplay between these factors within different domains.

(3) Both current MMs and reference architecture models focus more on operation/process, technology and product but less on the culture domain.

The MM domains that are most commonly addressed in the reference architecture models of I4.0 are operation/process, technology and product. Table 5 shows that RAMs include all of the operation/process subdomains. Furthermore, IVRA includes all sub-domains in the product and technology domains. Conversely, the culture domain is the least addressed in the reference architecture models. Although three of the five reference models included collaboration in the cultural domain, none discussed the willingness to change. Likewise, in the organisational governance domain, IVRA is the only reference architecture model that discusses digital leadership capability, while others include factor strategy for I4.0.

Recommendations and proposed research direction: fostering cultural and organisational change.

As we investigated some of the non-technical/physical factors in MM domains that lack compatibility with current I4.0 reference architectures, it may indicate that organisations tend to prioritise the technical aspects of I4.0 implementation over the organisational and cultural changes. Integrating those factors in RAMs is valuable as a company's maturity for I4.0 includes all of them, while RAMs support the effective achievement of information integration and facilitate the success of the I4.0 transformation. A culture of innovation and openness to change is also crucial for successfully adopting and implementing I4.0 technologies and practices (Črešnar *et al.*, 2022). Organisations need to prioritise the development of a culture that supports the adoption of new technologies and practices to achieve the full benefits of I4.0 implementation (Alkhazaleh *et al.*, 2022).

Further research must focus on developing MMs and reference architecture models that pay more attention to the "culture" domain, including aspects such as organisational culture, collaboration and willingness to change. This research direction should explore how these cultural factors can be integrated into I4.0 initiatives and how reference architecture models can better address them.

(4) The aspects of reputable standard reference architecture focus on, and some limitations regarding what it lacks.

Standard Industry 4.0 reference architecture models typically focus on the technical aspects of I4.0, as shown in Table 4, such as communication protocols, information models and data exchange standards. They provide a high-level blueprint for designing and implementing an Industry 4.0 system. However, they may neglect non-technical or non-physical domains, such as organisational structure, human factors and culture. These models may not be flexible enough to meet the unique needs of different organisations or industries. Additionally, while several internal factors have been broadly investigated in the literature, only a few discuss external factors.

Recommendation and proposed research directions: the importance of comprehensive assessment and external factors analysis that impact I4.0 adoption.

After implementing a comprehensive assessment based on their needs, companies can employ reference architecture models that allow flexibility to accommodate their specific requirements and their implementation pathway. This flexibility should extend beyond technical components to encompass various organisational and cultural factors.

It is worth analysing other external factors, such as regulatory changes, community development and geopolitical events that impact I4.0 initiatives. As some countries regulate the use of some of the reference architecture models presented in this paper as their national standards, such as RAMI4.0 and IMSA, we found that in MMs development, there are also interventions from the government. SIRI (EDB, 2017), Industry4WRD (MITI, 2018) and INDI4.0 (MOI, 2018) are some of the MMs developed with government interventions. To some extent, these regulations and interventions are used as an accelerator for adopting I4.0 while supporting I4.0 adoptions with some policies and stimuli. Another sample of external factors is community development. Since community development can drive the self-development of innovations selected by collaboration (Wahyuningtyas *et al.*, 2022), it can also be considered an external influencing factor in I4.0 adoption.

5.2 Summary of contribution and implications

This study proposes a novel approach to aligning I4.0 capabilities with current, reputable standard reference architecture models. It involves analysing the alignment of I4.0 MMs and RAMs and can be used to enhance the needs of various companies' strategies. Such an analysis can be valuable for researchers and practitioners looking to understand the current state of the art in I4.0 MMs and RAMs. Furthermore, it helps them choose and use the suitable MM and RAM.

The following theoretical implication of this paper is that it contributes to the literature on aligning capabilities with implementation strategies. Whereas previous studies suggest that companies need to choose and implement I4.0 MM to match their strategy carefully (Angreani *et al.*, 2020; Elibal and Özceylan, 2021; Şener *et al.*, 2018), this study shows manufacturing strategies that were implemented using RAM can be aligned with I4.0 capabilities by mapping the factors identified in MMs to the aspects of RAMs.

The next practical implication is that the study's result can help develop a framework that aligns I4.0 MMs with RAMs. This alignment can help organisations develop a more coherent and integrated approach to implementing I4.0 capabilities that are aligned with the standard reference architecture they use and their overall business strategy. Such a framework can be particularly useful for organisations that are just starting their I4.0 journey and use it as guidance to align their capabilities with the Industry 4.0 standard reference architectures. It would involve identifying the common pitfalls organisations encounter when implementing I4.0 and proposing solutions to overcome them.

6. Conclusions and limitations

This study seeks to systematise the existing scientific knowledge regarding I4.0 MMs. In particular, this paper aims to provide an overview of current I4.0 MMs and review their alignment with the most recognised RAMs.

In general, we define a new taxonomy with six domains of the MM for I4.0: technology, product, operation/process, resource, culture and organisational governance. We found that only a few current maturity models include all those domains. We also found a lack of alignment between I4.0 MMs and current reputable RAMs. This fact can be justified by the fact that RAMs are more focused on technology and physical matters (Kagermann *et al.*, 2016), while a company's maturity measures technological capabilities and transforms their culture and organisational governance. In addition, the term industry 4.0 is sometimes misinterpreted by only focusing on a technical and technological perspective (Schuh *et al.*, 2020). Our study's results indicate that some factors receive more attention in the literature, namely the technology and operation/process domains. Indeed, the results of this study highlight specific gaps in the literature on I4.0, which lead to the six recommended directions for future research.

Apart from the theoretical implications, this work also has important practical implications. This work gives practitioners an overview of the most suitable MMs and RAMs for them. Based on the findings in this study, practitioners can use MMs that are appropriate to their business and choose the most suitable RAM for them, while combining more than one MM is also possible. Moreover, based on our analysis of the research findings, we suggest that companies should initiate the process by undertaking a thorough needs assessment using I4.0 MM to fully leverage the capabilities of RAM. This assessment should involve a thorough exploration of their specific needs, objectives and constraints.

As with any research, this study has some limitations. There could be a subjective bias in reading and selecting literature, as it was identified as a common issue in literature review papers (Garzoni *et al.*, 2020; Moeuf *et al.*, 2018; Wen *et al.*, 2012; Zheng *et al.*, 2020). Indeed, the criteria adopted in the literature review strategy, either exclusion or inclusion, were set according to the study's purpose and may have excluded useful articles for analysis. In this case, we may have omitted a small part of the literature after selecting a paper from Scopus, even though it is significantly populated. In addition, we did not include non-English articles, which raises the possibility that we did not examine some relevant references in this study. Another limitation of this paper is that we only aligned MMs to RAMI4.0, NIST-SME, IMSA, IIRA and IVRA, which were mentioned in several literature reviews. Even though these five RAMs are the current most recognised RAMs, we did not search for and discuss other RAMs discussed in previous studies.

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Supplementary material

The supplementary material for this article can be found online.

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