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A Novel Lean-Centric Readiness Model for Harnessing Lean Capabilities in Industry 4.0 Digital Technology Adoption

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Abstract:

Purpose: This study addresses the gap in existing Industry 4.0 (I4.0) readiness models, which overlook the foundational role of lean manufacturing (LM) in enabling digital technology adoption. It explores how lean capabilities enhance I4.0 readiness, supporting manufacturing firms leveraging their prior investments in LM for digital transformation.

Design/methodology/approach: This study adopts a systematic literature review (SLR) of 20 I4.0 readiness models to investigate the extent to which LM concepts are incorporated. To reinforce the analysis, a content analysis was conducted using a comprehensive spreadsheet that captured each model's dimensions. Key readiness dimensions were synthesised alongside assimilated lean concepts. Based on this analysis, a novel lean-centric I4.0 readiness model was developed, comprising six core dimensions and 39 sub-dimensions, which reflect essential lean capabilities aligned with digital transformation.

Findings: The findings reveal a substantial gap in existing I4.0 readiness models in explicitly incorporating core LM concepts. The proposed lean-centric I4.0 readiness model emphasises the need to balance technology, organisational, and process maturity enablers, contrary to models prioritising technological factors alone.

Research limitations/implications: The review is based on the published literature on manufacturing where LM practices may have different degrees of adoption in different manufacturing sectors. Also, the review was confined to the literature published in English, which may limit the generalisability to other regions. Future research can validate this model empirically across diverse manufacturing contexts.

Practical implications: The novel lean-centric I4.0 readiness model developed in the study enables manufacturing firms to assess readiness through a lean lens. It can also aid their understanding of how their existing LM practices enable digital transformation readiness. The model facilitates strategic decision-making, resource allocation, and priority setting, reducing the risk of digital transformation failures.

Originality/value: This is the first study to examine I4.0 readiness models for the extent of integration of LM concepts. The proposed lean-centric I4.0 readiness model with a range of dimensions and sub-dimensions enriches the in-depth integration of LM and I4.0 literature. It offers a foundation for further empirical studies on lean-centric readiness assessment.

Keywords: industry 4.0, smart manufacturing (SM), readiness models (RM), lean manufacturing (LM), technology adoption

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1. Introduction

Manufacturing capabilities are undoubtedly recognised as crucial for economic performance (Anil, Reinhard & Jatin, 2016; Qin, Liu & Grosvenor, 2016) where manufacturing firms are continuously under pressure to elevate product quality, streamline cost efficiency, and reduce lead times (Alifiya & Singgih, 2019; Gomathi-Prabha, Rajamohan, Manikandan & Petluru, 2022). These challenges, coupled with evolving market needs and volatile customer demands, necessitate continuous technology upgrades in manufacturing (Lindquist, 2024; Schwab, Gold & Reiner, 2019).

Industry 4.0 (I4.0), also known as the fourth industrial revolution has revolutionized manufacturing by leveraging the Internet of Things (IoT) and advancements in information and communication technology (ICT) (Montasari, 2023; Rajamanickam, Royan, Ramaswamy, Rajendran & Vadivelu, 2023). It enables real-time decision-making, increasing productivity, agility, and flexibility and leverages information technologies and industrial automation to offer enhanced flexibility, scalability, and reduced resource wastage (Brettel, Friederichsen, Keller & Rosenberg, 2014; Dassisti & De-Nicolò, 2012; Jamil, Pang & Cheng, 2023), thereby minimizing operational costs and achieving up to a 50% increase in productivity (Caylar, Naik & Noterdaeme, 2016).

Lean manufacturing (LM) is commonly adopted to enhance operations performance, where the integration of LM concepts with I4.0 technologies has emerged as a crucial strategy for the successful implementation of I4.0 in manufacturing firms (Saad, Bahadori, Bhovar & Zhang, 2023; Sanders, Subramanian, Redlich & Wulfsberg, 2017). Acting as a facilitator, LM overcomes barriers in the implementation of I4.0, thus initiating the adoption of this cutting-edge technology (Fortuny-Santos, López, Lujan-Blanco & Chen, 2020; Kamble, Gunasekaran & Sharma, 2018; Komkowski, Antony, Garza-Reyes, Tortorella & Pongboonchai-Empl, 2023). Previous studies have underscored lean as a foundational requirement in this integration process (Buer, Strandhagen & Chan, 2018; Ejsmont, Gladysz, Corti, Castaño, Mohammed & Martinez-Lastra, 2020; Sony, 2018; Staufen AG, 2016).

Various I4.0 readiness models have assessed the potential for I4.0 implementations but the integration of lean capabilities is under-researched (Hajoary, Balachandra & Garza-Reyes, 2023; Lokuge, Sedera, Grover & Dongming, 2019; Schumacher, Erol & Sihn, 2016). Previous literature reviews of I4.0 readiness models have focused on suggesting the I4.0 readiness and implementation framework (Ansari, Barati, Sadeghi-Moghadam & Ghobakhloo, 2023; Saleh & Ijab, 2023), dimensions (Hajoary, 2020; Hizam-Hanafiah, Mansoor-Ahmed & Nor-Liza, 2020), comparisons for organisations to choose and apply available models (Ünlü, Demirörs & Garousi, 2023) and social well-being perspective (Omar, 2021). Exploring the dimensions, applicability, and coverage of these models to understand how LM concepts have been integrated is required. Hence, this study aims to answer the following research questions (RQs):

RQ1: What are the characteristics of existing I4.0 readiness models?

RQ2: Do existing I4.0 readiness models incorporate lean concepts?

RQ3: How can existing lean concepts be integrated into I4.0 readiness models as enablers of I4.0 implementation?

Based on a systematic review of 20 readiness models from the peer-reviewed literature (2019-2023), this study identifies that most of the models include LM concepts at varying levels, but a limited number of readiness models explicitly recognise and incorporate the specific requirements of LM concepts. Further, the study identifies six core dimensions and 39 sub-dimensions, each representing vital facets of organisational preparedness for the I4.0 era and proposes a forward-looking lean-centric I4.0 readiness model for manufacturing firms. The findings contribute to both LM and I4.0 literature by providing valuable insights for manufacturing firms seeking to harmonise I4.0 implementation with lean concepts to promote more efficient and sustainable digital transformation.

The subsequent sections of this paper are organised as follows: Section 2 introduces the relevance and important concepts of lean and I4.0 and presents the background of the study. Section 3 outlines the literature review methodology and review principles, while Section 4 presents the findings and provides a comprehensive discussion and critical analysis of the different readiness models focused on lean concepts. Section 5 develops a lean-centric conceptual readiness model. Section 6 offers the conclusion and implications. Finally, Section 7 concludes the study by outlining the limitations, and future research directions.

2. Theoretical Background

2.1. Industry 4.0

Industry 4.0 characterises a significant advancement in production technologies (Boshnyaku, 2023; Xu, Xu & Li, 2018) with a primary goal of digital integration of physical and software systems, creating an environment where all members of the value chain are networked and share information (Awan, Sroufe & Bozan, 2022; Schlechtendahl, Keinert, Kretschmer, Lechler & Verl, 2015). This transformation results in intelligent products and production processes, enabling factories to anticipate future products and respond to complexity with cost and environmental considerations (Herrmann, Schmidt, Kurle, Blume & Thiede, 2014; Samaraz, 2023). The potential of I4.0, aiming to increase manufacturing efficiency, integrate systems, network products, and enhance service portfolios is widely recognised (Moon, Lee, Park, Kiritsis & von-Cieminski, 2018).

I4.0 has nine pillars of technology foundations: Internet of Things (IoT), Cloud computing, Vertical and horizontal system integrations, Big data analytics, Autonomous robots, Additive manufacturing, Simulations, Augmented reality, and Cyber security (Alcácer & Cruz-Machado, 2019; Rüßmann, Lorenz, Gerbert, Waldner, Justus, Engel et al., 2016; Shah, Chowdhry, Hussain, Nisar, Shaikh & Samo, 2023). Increased automation, self-optimisation of process improvements, improved preventative maintenance, and most crucially, a higher degree of efficiency and responsiveness to client requirements that were not before possible, are all outcomes of these technologies (Cortina, 2022).

Despite its popularity and recognised benefits of I4.0, implementations remain challenging for many firms due to the need for comprehensive integration of technological solutions. Despite various strategic initiatives and ongoing surveys and research projects, firms still struggle to fully adopt a holistic I4.0 approach (Bellantuono, Nuzzi, Pontrandolfo & Scozzi, 2021; Shafik & Case, 2022). Organisational factors such as people, business model transformation, strategic orientation, maturity of capabilities and culture pose additional hurdles (Bressanelli, Adrodegari, Perona & Saccani, 2018; Ingaldi & Ulewicz, 2020; Metallo, Agrifoglio, Schiavone & Mueller, 2018; Moeuf, Pellerin, Lamouri, Tamayo-Giraldo & Barbaray, 2018; Prause, 2019; Tirabeni, De-Bernardi, Forliano & Franco, 2019). Hence, a proper methodology for readiness assessment concerning smart manufacturing (SM) is considered as a requirement before embarking on the transition towards I4.0 (Amaral & Peças, 2021; De-Carolis, Macchi, Negri & Terzi, 2017).

2.2. Lean Manufacturing

Lean is defined as a dynamic process for continuous improvement through waste elimination (Womack, Jones & Roos, 1990). Womack et al. (1990) describe it as a set of methods and tools to identify and eliminate inefficiency and waste without additional resources. LM is a systematic methodology for waste reduction (Pramanik, Mukherjee, Pal, Upadhyaya & Dutta, 2020; Shah & Ward, 2003) and continuous improvement and has gained significant recognition as a business strategy (Sony, 2018; Womack et al., 1990). Lean emphasizes efficient resource utilization to create value for consumers by eliminating wasteful activities in the value system (Sriparavastu & Gupta, 1997; Womack et al., 1990).

The global adoption of LM consistently demonstrates operational, financial, and environmental improvements for companies (Chavez, Gimenez, Fynes, Wiengarten & Yu, 2013; Wickramasinghe & Wickramasinghe, 2017). Studies highlight its positive impact on firm performance, operational efficiency, and waste reduction (Alcaraz, Maldonado, Iniesta, Robles & Hernández, 2014; Negrão, Godinho Filho & Marodin, 2017; Vinodh, Kumar & Vimal, 2014). Lean optimizes processes and inventory, reducing manufacturing time, enhancing resource utilization, and enabling quality production at the lowest cost (Potdar, Routroy & Behera, 2017). Successful implementation results in enhanced resource utilization (Nallusamy, 2016), waste reduction (Jasti & Kodali, 2019), and improved competitive advantage (Psomas, 2021; Tiwari, Sadeghi & Eseonu, 2020).

2.3. Lean Manufacturing and Industry 4.0

A synergistic relationship between lean and I4.0, with their integration positively impacts business performance (Osti, 2020). While lean emphasizes human-centred approaches and continuous improvement to eliminate waste (Rüttimann & Stöckli, 2016), I4.0 leverages advanced technologies like IoT and automation for highly networked production systems (Pagliosa, Tortorella & Ferreira, 2021). Despite their differences, both share common goals of improving process flexibility and productivity (Rüßmann et al., 2016) and most believe they can be effectively combined (Buer, Semini, Strandhagen & Sgarbossa, 2021; Satoglu, Ustundag, Cevikcan & Durmusoglu, 2018).

Lean concepts are considered as prerequisites for successful I4.0 implementation (Buer et al., 2018; Ejsmont et al., 2020; Sony, 2018; Staufen AG, 2016). Some argue that companies aspiring for high I4.0 standards often need a certain level of maturity in lean management (Pavlovic, Milosavljevic & Mladenovic, 2020; Rossini, Costa, Tortorella & Portioli-Staudacher, 2019). Automating processes without lean improvements may exacerbate inefficiencies (Krishnan, 2013), emphasizing the importance of integrating I4.0 technologies strategically into established LM concepts (Satoglu et al., 2018). Overall, a foundational level of lean maturity is essential for the effective integration of I4.0 technologies (G. L. Tortorella, Rossini, Costa, Portioli-Staudacher & Sawhney, 2021), as a deficiency in LM concepts can hinder the realization of I4.0 benefits and lead to managerial dissatisfaction and financial losses (Ding, Ferràs-Hernández & Agell-Jané, 2023). Table 1 presents LM concepts that have been recognised as prerequisites for I4.0 implementation (Buer et al., 2018; Dombrowski, Richter & Krenkel, 2017; Kolberg & Zühlke, 2015; Saxby, Cano-Kourouklis & Viza, 2020).

LM Concept	How LM Facilitates I4.0	Source(s)
Waste Reduction	LM reduces waste and process variation by eliminating non-value-added activities, serving as a foundation for I4.0. It ensures the integration of I4.0 solutions conducive to value creation, preventing digitalizing waste in operations.	Dombrowski et al. (2017), Mayr, Weigelt, Kühl, Grimm, Erll, Potzel et al. (2018), Vita (2018)
Process Optimisation and Continuous Improvement	LM simplifies processes, enabling efficient use of digital tools. It fosters a culture of continuous improvement where staff actively seek enhancements, crucial for the effective implementation of I4.0, which demands constant adaptation to new technologies.	Dombrowski et al. (2017); Mayr et al. (2018) Osti (2020), Saxby et al. (2020)
Data-driven Decision-Making	I4.0 generates vast data requiring real-time utilization and fostering a data-driven culture, aligning well with LM. Ensuring efficient information flow and accurate data are crucial for success in both I4.0 and lean methodologies.	Arati (2020), Palange & Dhatrak (2021)
Worker Mindset, Employee Training and Upskilling	LM emphasizes employee development and cross-training to prepare the workforce for I4.0 challenges. Worker mindset, defined by continuous improvement and innovation, is crucial for a smooth transition to I4.0 technologies.	Grant & Hallam (2016), Morrar, Arman & Mousa (2017), Palange & Dhatrak (2021)
Employee Engagement	Engaged employees are key to effective technology implementation. Lean methodologies enhance problem-solving skills and promote collaboration, facilitating quick access to data and efficient problem resolution, crucial for I4.0 systems optimization.	Buess (2021), Pereira, Dinis-Carvalho, Alves & Arezes (2019)
Leadership Commitment	Strong commitment from top management is vital for successful lean transformation and deployment of I4.0 technologies, driving cultural changes and investments necessary for implementation.	Tissir, El-Fezazi & Cherrafi (2020)
Culture of Adaptability	LM fosters adaptability and flexibility, essential for embracing technological innovations of I4.0 and adjusting to new work norms effectively.	Mayr et al. (2018)

LM Concept	How LM Facilitates I4.0	Source(s)
Cross-Functional Collaboration	Promoting collaboration between departments facilitates holistic process improvement and technology integration, beneficial for effectively adopting various I4.0 technologies across the organisation.	Bettiol, Capestro, Di-Maria & Grandinetti (2023); Grant & Hallam (2016)
5S Methodology	Implementing 5S concepts creates a clean and organized workplace, vital for the efficient deployment of I4.0 concepts, simplifying integration and maintenance of advanced technologies.	Kolberg & Zühlke (2015), Mrabti, Bouajaja, Hachicha & Nouri (2023)
Standardisation	Lean's standardisation of processes supports I4.0 by simplifying communication and integration. It lays the foundation for scalability and seamless integration of I4.0 technologies.	Kolberg & Zühlke (2015); Laaper & Kiefer (2020), Walentynowicz & Pienkowski (2020)
Visual Management	Visual management techniques enhance transparency and facilitate real-time data interpretation, aligning with the requirements of I4.0.	Osti (2020), Staufen AG (2016); Stefan & Schneider (2015); Walentynowicz & Pienkowski (2020)
Just-in-Time (JIT) and Kanban	JIT production and Kanban systems reduce inventory and waste, preparing for the real-time data-driven approach of I4.0.	Osti (2020), Wagner, Herrmann & Thiede (2017)
Value Stream Mapping (VSM)	VSM analyses material flow and identifies process waste, aiding in the preparation for digital technology integration.	Lugert, Völker & Winkler (2018); Wagner, Herrmann & Thiede (2018), Bega, Sapel, Ercan, Schramm, Spitz, Kuhlenkötter et al. (2023), Mayr et al. (2018)
Total Productive Maintenance (TPM)	TPM focuses on proactive equipment maintenance, aligning with the predictive maintenance features of I4.0.	Sanders et al. (2017), Tortorella, Saurin, Fogliatto, Tlapa, Moyano-Fuentes., Gaiardelli et al. (2022)
Quality Management	Lean's emphasis on quality control aligns with the data-driven quality assurance capabilities of I4.0, facilitating defect prevention and process improvement.	Osti (2020), Walentynowicz & Pienkowski (2020)
Automation	Lean's autonomation concept and waste-minimized processes provide a foundational framework for I4.0's enhanced automation, indicating an evolutionary relationship with Jidoka concepts.	Buer et al. (2018), Osti (2020), Vita (2018)
Lean Supply Chain	Extending lean concepts to the supply chain enhances efficiency and adaptability, supporting the process integration of I4.0.	Lasi, Fettke, Kemper, Feld & Hoffmann (2014); Posada, Toro, Barandiaran, Oyarzun, Stricker, De-Amicis et al. (2015); Wang, Wan, Li & Zhang (2016), McDermott, Antony, Sony & Swarnakar (2023)

Table 1. LM and I4.0

2.4. Readiness Models

Readiness assessments encompass evaluating a company's preparedness for significant changes or new capabilities, products, or business models (Koh, 2022). In the context of I4.0 implementation, firms must conduct readiness assessments before embarking on this transformative journey (Lucato, Pacchini, Facchini & Mummolo, 2019; Schumacher et al., 2016). Organisations can utilise I4.0 readiness assessment models to evaluate their status which leverages the conversion. These models compare the company's current state with the ideal standard, enabling necessary actions for improvement aligned with smart paradigms (Ejsmont et al., 2020; Tissir, Cherrafi, Chiarini, Elfezazi & Bag, 2023). They facilitate the development process (Hizam-Hanafiah et al., 2020; Schumacher et al., 2016), embodying a series of levels evaluating the present status of a company's conversion towards increased agility, focusing on processes, systems, and technologies (Becker, Knackstedt & Pöppelbuß, 2009; Gottschalk, 2009; Kazanjian & Drazin, 1989; Mrugalska & Ahmed, 2021).

3. Research Methodology

This study utilises an SLR method to ensure methodological rigour and transparency. The SLR is a recognised method for critically evaluating research findings and answering explicitly stated research questions (Denyer & Tranfield, 2009; Tranfield, Denyer & Smart, 2003). This research adheres to the conventional five-step SLR process. These phases include (1) formulation of research questions; (2) identification of relevant studies; (3) selection and evaluation of pertinent studies; (4) analysis and synthesis of findings; and (5) reporting of results (Denyer & Tranfield, 2009).

3.1. Data Sources

The second stage involves the identification of pertinent studies relevant to our research inquiries including the selection of appropriate search engines and the formulation of precise search queries (Denyer & Tranfield, 2009; Tranfield et al., 2003). The scope of our study lies at the intersection of I4.0 and readiness. Thus, we employed keywords identified from a review of the extant literature on I4.0, and readiness models (Bibby & Dehe, 2018; Dutta, Kumar, Sindhwani & Singh, 2020; Hajoary, 2020; Hajoary et al., 2023; Leyh, Schäffer, Bley & Forstenhäusler, 2016; Lokuge et al., 2019; Mittal, Khan, Romero & Wuest, 2018; Schumacher et al., 2016; Stentoft, Adsbøll-Wickstrøm, Philipsen & Haug, 2020), coupled with brainstorming sessions among authors and search strings were developed.

The search strategy was developed to yield accurate and comprehensive results, to avoid false search outcomes (Denyer & Tranfield, 2009; Tranfield et al., 2003). Search terms include "self-assessment", "readiness", "Industry 4.0", "Industrie 4.0", "I4.0", "4th Industrial Revolution", "Fourth Industrial Revolution", "Smart factory", "Smart manufacturing", "Smart production", "Digitalisation", "Digitalization", "Digital technology", and "Digital transformation". No restrictions were imposed on publication dates, as this could potentially constrict the scope of our findings. Given the divergent syntax employed by the databases, the keywords were logically conjoined using Boolean operators applicable to each database. This search process was executed in September 2023 on multiple scholarly databases and search engines (Scopus, ProQuest, EBSCO, Web of Science and Google Scholar search engine) to mitigate the probability of overlooking relevant articles due to variations in publications (Lun, D'Innocenzo, Smarra, Malavolta & Di-Benedetto, 2019). The main search terms employed in these search strings were refined through multiple pilot tests carried out across the four databases, thereby mitigating the potential for false search outcomes and ensuring the discovery of significant scholarly works (Denyer & Tranfield, 2009; Durach, Kembro & Wieland, 2017). Below is an example of a search query employed in the ProQuest database.

("Readiness" OR "Self-Assessment") AND ("Industry 4.0" OR "Industrie 4.0" OR "I4.0" OR "4th Industrial Revolution" OR "Fourth Industrial Revolution" OR "Smart factor*" OR "Smart manufacturing" OR "Smart production" OR "Digitali*" OR "Digital tech*" OR "Digital transformation").

3.2. Screening

To minimise systematic errors and researcher bias in the article screening process, we developed a literature review screening protocol following Popay, Roberts, Sowden, Petticrew, Arai, Rodgers et al. (2006), Denyer and Tranfield (2009) and Tranfield et al. (2003). This protocol outlined the scope, strategy, and data extraction methodology as illustrated in Figure 1 and Table 2. Following the process applied by Mittal et al. (2018), Tripathi and Gupta (2021), and Cherrafi, Garza-Reyes, Belhadi, Kamble and Elbaz (2021) the primary inclusion criteria were the type of literature and language where we included articles published in peer-reviewed journals and written in English. In contrast, grey literature, including conference papers, theses, book chapters, lecture notes, reports, etc., and industry-backed white papers, were excluded due to their limited data availability, comparatively informal nature, and potential bias introduced by the commercial interests of the firms publishing them. These exclusion and inclusion criteria were established through consensus among the authors to mitigate the potential biases associated with single decision-making (Thomé, Scavarda & Scavarda, 2016).

In the initial search phase, we identified a total of 1,064 papers, with 106 from Web of Science (WoS), 146 from EBSCO, 381 from Scopus, and 431 from ProQuest. Subsequently, we conducted three elimination rounds following Denyer and Tranfield (2009), Popay et al. (2006) ensuing review. In the first elimination round, duplicates were removed, leaving us with 874 peer-reviewed articles. The second elimination phase aimed to determine the studies lacking sufficient relevance for inclusion (Okoli & Schabram, 2015) by analysing the titles and abstracts. This process identified 68 articles relevant to the manufacturing industry. Articles primarily concerned with enterprise-level manufacturing readiness, as opposed to readiness at the national, regional, city, or component level, were included. Additionally, articles focusing exclusively on specific aspects of I4.0 (e.g., supply chain, human resources) other than technology or readiness were excluded. Lastly, readiness models lacking adequate descriptions of their levels and dimensions were also excluded. Finally, to ensure comprehensive coverage, we conducted a search on Google Scholar, considering saturation to be reached when no new peer-reviewed papers were found. After evaluating titles and abstracts, we selected five articles for in-depth examination, bringing the total number of papers reviewed to 73. Table 2 summarizes the parameters used for the query.

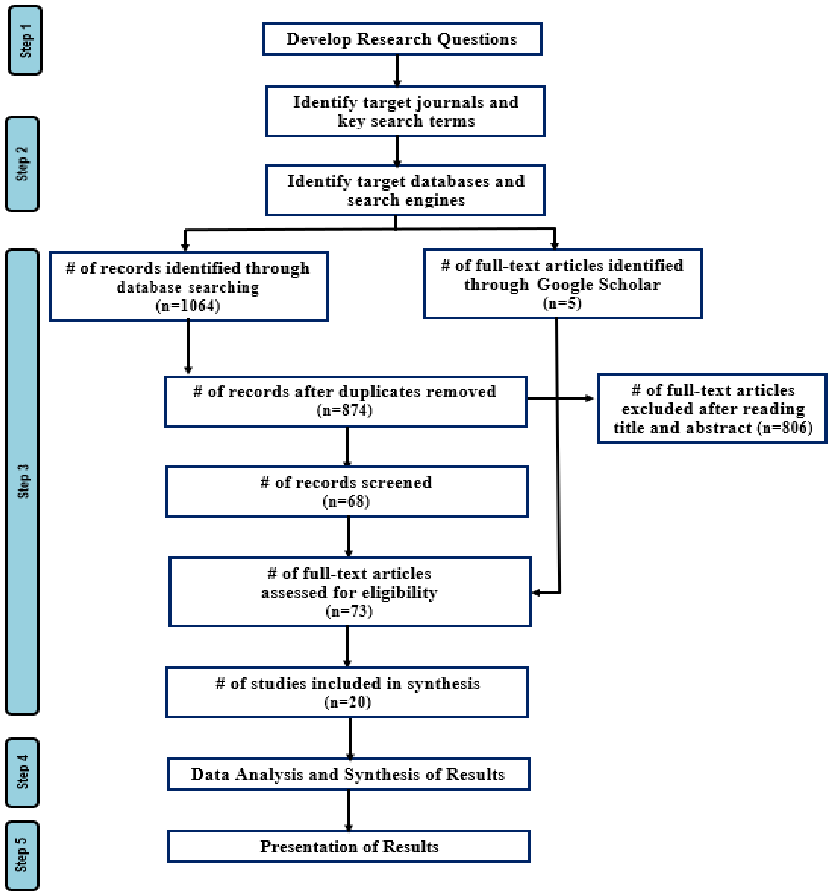

Figure 1. Systematic Review Methodology

The third elimination round encompassed the final selection of the retrieved documents. It was a collective exhaustive process between the authors involving a thorough examination of the full texts, with a focus on retaining literature directly associated with the research topic and the research questions of the systematic review. During this phase, papers that lacked sufficient background information on I4.0 readiness models (including their scale) and model dimensions were excluded. Despite the careful selection of query keywords for accurate results, only 20 papers, that met the criteria of containing an I4.0 readiness model or scale, were deemed suitable for further investigation.

3.3. Data Analysis

The subsequent phase entailed the establishment of correlations between defined LM prerequisites and I4.0 dimensions by elucidating how lean concepts are integrated into each readiness model. To reinforce this, content analysis, a structured spreadsheet was developed, encompassing the primary focus, contributions, dimensions, and research gaps of each paper. The predominant dimensions and levels encompassed in the readiness models were identified, in conjunction with the assimilated lean concepts.

Source	Search String	Title	Abstract	Keywords	After removing duplicates inside the source	After removing duplicates using Endnote	After reading the title and abstracts	Selected to analyse
ProQuest	(“Readiness” OR “Self-Assessment”) AND (“Industry 4.0” OR “Industrie 4.0” OR “I4.0” OR “4th Industrial Revolution” OR “Fourth Industrial Revolution” OR “Smart factor*” OR “Smart manufacturing” OR “Smart production” OR “Digitali*” OR “Digital tech*” OR “Digital transformation”)	92	427	No option available	431	344	23	4
SCOPUS	Full string	381			381	314	28	8
ESBCO	Readiness AND “Industry 4.0” Readiness AND “Industrie 4.0” Readiness AND “I4.0” Readiness AND “4th industrial revolution” Readiness AND “fourth industrial revolution” Readiness AND “Smart factor*” Readiness AND “Smart manufacturing” Readiness AND “Smart production” Readiness AND “Digital transformation” Readiness AND Digitali* Readiness AND “Digital technology” “Self-Assessment” AND “Industry 4.0” “Self-Assessment” AND “Industrie 4.0” “Self-Assessment” AND “I4.0” “Self-Assessment” AND “4th industrial revolution” “Self-Assessment” AND “fourth industrial revolution” “Self-Assessment” AND “Smart factor*” “Self-Assessment” AND “Smart manufacturing” “Self-Assessment” AND “Smart production” “Self-Assessment” AND “Digital transformation” “Self-Assessment” AND “Digitali*” “Self-Assessment” AND “Digital technology”	322 (Unrestricted / All fields)			146	140	7	1
Google Scholar	Full string	Unrestricted / All fields					5	2
WoS	Full string	106 (Unrestricted / All fields)			106	76	10	5
Total					1064	874	73	20

Table 2. Summary of the parameters used in the database searching

4. Results

4.1. Descriptive Analysis

Table 3 provides an overview of various readiness assessment models mined from the 20 different articles. Figure 2 outlines the publication years and shows that even though the I4.0 concept was initiated in 2011, there was no peer-reviewed comprehensive readiness model published for manufacturing until 2019. This shows the novelty of the concept.

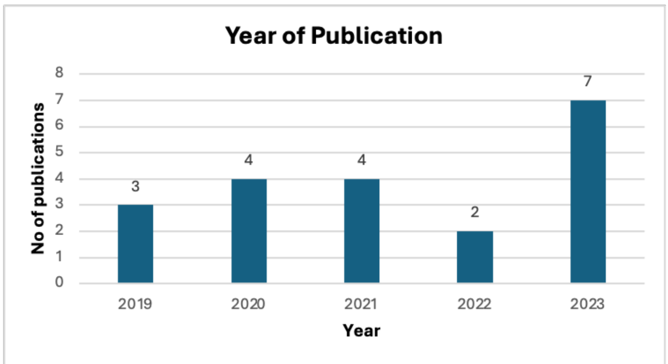

Figure 2. Year of Publication

Readiness Model #[1]	Author & Year[2]	Article Name / Model Name / Type of The Model[3]	Focus[4]	Main Contributions[5]	Dimensions / Sub-dimensions (Indicators) / Levels[6]	Gaps (Limitations)[7]
RM1	Lokuge et al. (2019)	Organizational readiness for digital innovation: Development and empirical calibration of a construct (Readiness model)	- The main focus is to propose a constructive multidimensional model for assessing organisational preparedness for digital innovations - Aims to provide a scale for businesses to track preparedness to utilise digital technologies	- Construct provides a tool for practitioners to evaluate their preparedness to innovate with I4.0 technologies and allocate resources and capabilities accordingly - Readiness construct can be applied to determine levels for comparison across departments, firms, or demographic categories	- Seven subconstructs (dimensions): "Resource readiness, IT readiness, Cognitive readiness, Partnership readiness, Innovation valance, Cultural readiness, and Strategic readiness" - 21 sub-dimensions / measures (indicators) - Levels not mentioned	- Small sample size and selection bias - Need to extend the generalizability of the model - Self-Reported Data - Lack of Comparative Analysis - Lack of validity - Limited Contextualization - Lack of in-depth analysis of the specific components and indicators - Limited exploration of the interactions between different subconstructs - Insufficient consideration of external factors influencing organisational readiness - Does not provide a roadmap on how to improve readiness for digital innovation
RM2	Maisiri & van-Dyk (2019)	Industry 4.0 Readiness Assessment for South African Industries (Readiness model)	- Focus is to investigate the preparedness of South African businesses to implement I4.0	- Study identifies significant shortfalls in Industry 4.0 strategy - Provides insights into the skills requirements for I4.0, which can guide future training and development efforts	Six dimensions (categories): "Organisational strategy, Organisational infrastructure, Smart operations, Smart products, Data-driven services, and Employees" - 14 sub-dimensions (sub-categories) - 24 indicators - Six Levels: "Outsider, Beginner, Intermediate, Experienced, Expert, and Top performer"	- Convenience sampling - Small sample size, Limited industry representation - Inability to generalize the results - Self-reported data - Limited scope of dimensions - Does not provide a detailed analysis of each dimension or explore potential gaps within each dimension - Lack of comparison with other countries

Readiness Model #[1]	Author & Year[2]	Article Name / Model Name / Type of The Model[3]	Focus[4]	Main Contributions[5]	Dimensions / Sub-dimensions (Indicators) / Levels[6]	Gaps (Limitations)[7]
RM3	Pacchini, Lucato, Facchini & Mummolo (2019)	The degree of readiness for the implementation of Industry 4.0 (Readiness model)	- A structured method for evaluating the degree of preparedness to adopt I4.0 principles and practices	- Modifying the SAE J4000 standard to encompass I4.0 concepts	- Eight technology enablers: "Big data, Internet of Things (IoT), Cloud computing, Autonomous robots, Additive manufacturing, Cyber-physical systems, Augmented reality, and Artificial intelligence" - Model does not explicitly mention the number of indicators or sub-dimensions - Six Levels: Embryonic, Initial, Primary, Intermediate, Advanced, Ready	- Considered only Technology dimensions, Lack of organisation and operations dimensions - No details about items and development process presented. - Based on the SAE J4000 standard for measuring the application of LM which may not include other industry characteristics - Lack of validation and generalisability - Interrelationships among enabling technologies can influence the degree of readiness - Model doesn't include lean concepts
RM4	Chonsawat & Sopadang (2020)	Defining SMEs' 4.0 Readiness Indicators (Readiness model)	- Focus is on proposing a set of I4.0 readiness indicators for SMEs - Model is intended to help decision-makers evaluate readiness for I4.0 and identify areas for improvement	- Identifies 34 critical aspects that influence the readiness of SMEs for I4.0 through a bibliometric analysis of the literature - Study highlights the need for Industry 4.0 management to focus on supporting the capability scale of SMEs	- Five dimensions: "Organisational Resilience, Infrastructure System, Manufacturing System, Data Transformation, and Digital Technology" - 23 Sub-dimensions (indicators) - 4 Levels: "Not achieved, Partially achieved, Achieved, Fully achieved"	- Very small sample size (1) - Results may not be generalizable to other industries or geographical locations - Lack of external validation - Lack of identifying potential challenges or barriers in implementing the readiness indicators - Does not provide a detailed discussion on how the readiness indicators could be used in practice by SMEs
RM5	Sony & Aithal (2020)	Developing an Industry 4.0 Readiness Model for Indian Engineering Industries (Readiness model)	- The focus is to develop a multi-dimensional I4.0 readiness framework specifically for Indian Engineering Industries	- Model aims to help organisations address potential pitfalls, choose resource allocation, manage employee skills, and understand their present state and future goals - The model emphasises the need for comprehensive assessment, consensus discussions, and improvement in each dimension to ensure the successful execution of I4.0	- Six dimensions: "Organisational strategy, Digitization level of the industry, Digitization level of supply chain, Level of smart products, Employee adaptability with Industry 4.0 skills, and Top management support and leadership" - Sub-dimensions (indicators) are not mentioned - No specific mention of levels or stages	- Does not provide real-world scenarios or case studies to empirically validate the effectiveness of the proposed readiness model - Lack of generalizability - Model lacks reliance on existing theories - Lack of Information on the dimensions - Weighting of dimensions not defined - Model relies on self-assessment, which might result in inflated scores due to socially desirable responding

Readiness Model #[1]	Author & Year[2]	Article Name / Model Name / Type of The Model[3]	Focus[4]	Main Contributions[5]	Dimensions / Sub-dimensions (Indicators) / Levels[6]	Gaps (Limitations)[7]
RM6	Pirola, Cimini & Pinto (2020)	Digital readiness assessment of Italian SMEs: a case-study research "Digital Readiness Level 4.0 (DRL 4.0)" (Readiness model)	- Focuses on overcoming two major gaps: models' rigidity, and lack of focus on SMEs - Aims at both strategic and operational levels and technology implementation	- Modularity feature of the DRL 4.0 Model allows for the exclusion of non-applicable technologies or processes and thus provides a more accurate assessment of each company's readiness	- Five dimensions: "Strategy, People, Processes, Technology and Integration" - 24 indicators (sub-dimensions) - Five levels: DRL 1-5	- Identifies a need to categorize groups of firms with similar profiles and behaviours, and to define specific roadmaps and action steps to drive the transition - Limited sample size - Lack of generalizability - Self-reported data may introduce bias or inaccuracies - Limited external validity - the study does not compare the DRL 4.0 model with other existing models
RM7	Axmann & Harmoko (2020)	Industry 4.0 Readiness Assessment: Comparison of Tools and Introduction of New Tool for SME (Readiness model)	- The importance of data quality, data sharing, data storing, and data processing as key categories for assessing I4.0 readiness - Emphasises the importance of developing assessment tools specifically tailored for SMEs	- SWOT analysis used to evaluate the existing assessment models. This analysis serves as a basis for the development of the new model.	- Three clusters: "Data, Software, and Hardware" - 12 categories (dimensions): "Data sharing, Data storage, Data quality, Data processing, Product design and development, Smart material planning, Smart production, Smart maintenance, Smart logistics, IT security, Machine readiness, and Machine communication" - 60 indicators (sub-dimensions) - Five levels	- Lack of existing models analysed in the literature review - Model is not empirically validated - Comprehensive development roadmap is missing
RM8	Chonsawat & Sopadang (2021)	Smart SMEs 4.0 Maturity Model to Evaluate the Readiness of SMEs Implementing Industry 4.0 "Smart SMEs 4.0" (Readiness model)	- To evaluate the current capabilities of these enterprises and guide them in implementing I4.0 effectively	- Model that can assess the readiness of SMEs to enter the I4.0 and guide them to implement the I4.0 efficiently - "People Capability and Manufacturing and Operations" are the main dimensions	- Five dimensions: "Manufacturing and operations, People capability, Technology-driven process, Digital support, Business and organisation strategies" - 43 sub-dimensions - Five levels: "Level 1: Initial, Level 2: Managed, Level 3: Defined, Level 4: Qualitatively Managed, Level 5: Optimizing"	- Lack of detailed explanation of the methodology - Lack of comparison with existing maturity models - Limited discussion on the practical implications and implementation challenges - Limited scope of the case studies (2), more empirically validated evidence needed - Lack of generalizability - Confusing and duplicated sub-dimensions

Readiness Model #[1]	Author & Year[2]	Article Name / Model Name / Type of The Model[3]	Focus[4]	Main Contributions[5]	Dimensions / Sub-dimensions (Indicators) / Levels[6]	Gaps (Limitations)[7]
RM9	Hoa & Tuyen (2021)	A Model for Assessing the Digital Transformation Readiness for Vietnamese SMEs (Readiness model)	- Develop an empirical model for assessing the I4.0 readiness of SMEs	- Study assesses the influence of the preparedness of Vietnamese SMEs for digital transformation on the sustainability of their enterprise expansion - Model classifies enterprises into "Newcomers," "Learners," and "Leaders" based on their use of I4.0 concepts	- Four dimensions: "Enterprise Management, Productivity Management, Digital Transformation Platform, Smart Manufacturing" - Three levels of readiness for digital transformation: "High, medium, and low" - 16 Sub-dimensions (indicators) - 3 Levels: "Newcomers, Learners, and Leaders"	- Lack of generalizability to other countries - Lack of Comparative Analysis - Self-reported data may be subject to response bias - Further study is needed to validate the accuracy and usefulness of the model in real-world scenarios
RM10	Antony, Sony & McDermott (2023)	Conceptualizing Industry 4.0 Readiness Model Dimensions: An Exploratory Sequential Mixed-Method Study (Readiness model)	- Dimensions of the I4.0 readiness model is conceptualized - Evaluates their criticality in different sectors and types of organisations	- Study provides a framework for evaluating I4.0 readiness before the deployment of digital technologies - Identifies the critical factors that substantially impact the successful implementation of digital technologies	- 10 dimensions: "Technology readiness, Employee adaptability with Industry 4.0, Smart products and services, Digitalisation of supply chains, Extent of the digital transformation of the organisation, Readiness of Industry 4.0 organisation strategy, Innovative Industry 4.0 business model, Leadership and top management support for Industry 4.0, Organisational culture, and Employee reward and recognition systems" - No sub-dimensions or indicators mentioned - No levels mentioned	- Model does not provide a multidimensional item scale for measuring the dimensions of the I4.0 readiness - Lack of Empirical Validation - Lack of comparative analysis - Model may not be generalizable to other countries or regions

Readiness Model #[1]	Author & Year[2]	Article Name / Model Name / Type of The Model[3]	Focus[4]	Main Contributions[5]	Dimensions / Sub-dimensions (Indicators) / Levels[6]	Gaps (Limitations)[7]
RM11	Benešová, Basl, Tupa & Steiner (2021)	Design of a business readiness model to realise a green industry 4.0 company (Readiness model)	- Developing a readiness model for I4.0 regarding green attributes	- Evaluate the readiness model based on a questionnaire survey - Model analyses financial resources, human resources, equipment, technology, products, and services	- Five dimensions: "Strategy and leadership, Company resources, Technology, Product and services, Business processes" - Sub-dimensions are not mentioned - Six levels or stages: Outsider, Beginner, Intermediate, Upper Intermediate, Advanced, Expert	- Small sample size, may limit the generalizability - Study focused on firms in the electronics and transformers production industry - Response bias of self-reported data - Subjectivity in evaluation weights and scores to different dimensions and questions - Lack of Comparison with other models
RM12	Mansoor-Ahmed, Hizam-Hanafiah, Nor-Liza, Mohd-Helmi & Muhammad-Shahar (2021)	Industry 4.0 Readiness of Technology Companies: A Pilot Study from Malaysia (Readiness model)	- The focus of the model is to evaluate the preparedness of technology firms in Malaysia towards I4.0 and to identify the key areas that need to be addressed to improve their readiness	- Model covers factors such as the level of implementation of I4.0 technologies, the degree of digitalisation, and the level of employee skills and training - A 5-point Likert scale is used (1-Strongly Disagree and 5-Strongly Agree).	- Seven key areas: "Market pressure, Risk-taking, Knowledge, Management support, Competencies, Motivation, and Freedom" - Sub-dimensions are not mentioned - Does not explicitly mention specific levels or stages in the proposed model	- Survey-based and response bias - Lack of empirical validation, and detailed analysis - Lack of comparative analysis - Model may not be generalizable to other countries or regions - Insufficient Exploration of key areas
RM13	Felippes, da-Silva, Barbalho, Adam, Heine & Schmitt (2022)	3D-CUBE readiness model for industry 4.0: technological, organizational, and process maturity enablers "3D-CUBE" (Readiness model)	- Aims to address the shortcomings and limitations of existing models	- Emphasises the need for maturity to be considered as an input dimension rather than an output - Discusses the importance of human factors, such as training, communication, and a culture of innovation in implementing I4.0	- Three dimensions: "Organisational enablers, Technological enablers, and Process Maturity" - Six sub-dimensions and 21 elements - Six levels: 0-5	- Empirical validation and real-world implementation missing - Scalability or adaptability of the model to different types of manufacturing companies is not addressed - Lack of standardised approach for measuring the maturity levels of the dimensions and enablers
RM14	Monshizadeh, Sadeghi-Moghadam, Mansouri & Kumar (2023)	Developing An Industry 4.0 Readiness Model Using Fuzzy Cognitive Maps Approach (Readiness model)	- Develop an I4.0 readiness model using fuzzy cognitive maps	- Develops a model that considers both technological and non-technological attributes - Model is statistically validated	- Three prime dimensions: "Operational, Organisation, and Technology level" - 16 sub-dimensions - Does not specify the levels or stages	- Reliance on Expert Judgments - Lack of generalizability and applicability to different businesses and contexts - Model does not consider the financial and economic aspects of I4.0 implementation - Limited data availability

Readiness Model #[1]	Author & Year[2]	Article Name / Model Name / Type of The Model[3]	Focus[4]	Main Contributions[5]	Dimensions / Sub-dimensions (Indicators) / Levels[6]	Gaps (Limitations)[7]
RM15	Annie-Pooi-Hang & Daisy-Mui-Hung (2022)	Driving Factors of Industry 4.0 Readiness among Manufacturing SMEs in Malaysia (Readiness model)	- Proposes a theoretical framework for analysing the preparedness of businesses for I4.0 implementation, which includes four key factors: "Institutional support, Organisational capabilities, Market factors, and Perceived advantage". - Examine the moderating effect of the size of the company on the relationship between the driving factors and SMEs' preparedness for I4.0.	- Company size does moderate the relationship between institutional support and SMEs' preparedness - Company size does not moderate the relationship between organisational capabilities, perceived advantage, market factors and SMEs' preparedness	- Four key factors (dimensions): "Organisational capabilities, Institutional support, Perceived advantage, and Market factors" - 11 sub-dimensions, 69 items - Does not specify the levels or stages	- Small sample size - Lack of generalizability to other countries - Study is based on self-reported data, and may be subject to response bias - Model can explore other causes that motivate and encourage SMEs to prepare for I4.0
RM16	Hajoary et al. (2023)	Industry 4 0 maturity and readiness assessment an empirical validation using Confirmatory Composite Analysis (Both)	- To introduce a new multi-dimensional analytical model by providing a solid assessment framework and procedures	- Model uses IPMA and CCA analysis methods to validate the data - Providing practical recommendations for managers - Supply chain dimension critically, strongly influencing I4.0	- Six dimensions: "Manufacturing and operations, Business model, Products and services, Supply chain, Production technology, Strategy and organisation" - Thirty-two indicators (sub-dimensions) - Four levels: Level 1 to Level 4	- Need a roadmap to guide organisations towards digitalisation - Legal considerations and standardisation can be considered as variables
RM17	Govindan & Arampatzis (2023)	A framework to measure readiness and barriers for the implementation of Industry 4.0: A case approach (Readiness model)	- Proposes a model to evaluate readiness and barriers for the execution of I4.0	- Highlights the importance of leadership and organisational change management in adopting Industry 4.0 - Proposes a step-wise approach for businesses to implement I4.0 - Combines an assessment of a company's readiness level with its related barriers to I4.0 transformation	- Six readiness dimensions: "Business Models & Products, Market & Sales, Value Chains & Operations, IT infrastructure, Legal & Security, and Organisation & Strategy" - 36 readiness items - Four levels: 1 (minimum level of digitization) - 4 (maximum level of digitization)	- Only one case industry and the need for a more validated model - Limited generalizability of the findings to other industries or countries - Study relies on self-reported data, which may be subject to bias

Readiness Model #[1]	Author & Year[2]	Article Name / Model Name / Type of The Model[3]	Focus[4]	Main Contributions[5]	Dimensions / Sub-dimensions (Indicators) / Levels[6]	Gaps (Limitations)[7]
RM18	Zhao, Shao, Qi, Chu & Feng (2023)	A novel model for assessing the degree of intelligent manufacturing readiness in the process industry: process-industry intelligent manufacturing readiness index (PIMRI) (Readiness model)	- Tries to assess the degree of manufacturing preparedness in process engineering.	- Model provides a structured framework to direct firms in identifying their present stage and identifying areas for improvement	- Four races (dimensions): "Process, Organisation, Technology, and Intelligence" - Nine species (sub-dimensions) - 25 domains - Six levels: Initial, Planning, Canonical, Integrated, Optimizing, Leading	- Model is based on the subjective thinking of the evaluator - It may not be generalizable to other industries or geographical locations - Model does not offer a detailed approach to deal with the identified shortcomings
RM19	Sajjad, Ahmad, Hussain, Chuddher, Sajid, Jahanjaib et al. (2023)	Assessment by Lean Modified Manufacturing Maturity Model for Industry 4.0: A Case Study of Pakistan's Manufacturing Sector "Lean Modified Manufacturing Maturity Model for Industry 4.0 (LM4I4.0)" (Readiness model)	- Developing and validating a lean-modified manufacturing maturity framework for I4.0 in Pakistan's manufacturing sector - Lean philosophy is integrated into the IMPULS model	- LM4I4.0 model fills lean and I4.0 research spaces evaluated from major measurement tools and maturity levels perceptions from developing countries - Provides managerial implications for the senior management about the I4.0 process	- Seven dimensions: "Strategy, Smart factory, Smart product, Smart operations, Employee skill set, Data-driven services, and lean 4.0" - 41 sub-dimensions - Six readiness levels (0-5): "Outsider, Beginner, Intermediate, Experience, Expert, Top performer"	- Limited distribution of questionnaires, restricting the generalizability of the findings - Lack of empirical validation - Study does not include input from higher management in the decision-making process
RM20	Shukla & Shankar (2023)	Readiness assessment for smart manufacturing system implementation: multiple case of Indian small and medium enterprises (Readiness model)	- The main focus is to propose and test a readiness assessment framework for the implementation of SM systems in Indian SMEs	- The study contributes to the understanding of the readiness of Indian SMEs for SM implementation and provides a practical tool for assessing and improving their preparedness. - The dimensions in the model are ranked according to their significance - Incorporates the perspective of human behaviour and the "Stages of Change" concept	- 6 building blocks (dimensions): "Smart technology infrastructure, Economic, People & SM awareness, Organisation and culture management, Process capability, Supply chain management". - 22 sub-dimensions to assess the readiness - 5 stages: "Precontemplation, Contemplation, Preparation, Action, Maintenance"	- Small sample size (6) - Lack of empirical validation - Study is geographically focused - Lack of generalizability - Limited People management aspect - Potential bias in self-assessment

[1]This field provides a unique identifier for each study, making it easier to refer to specific studies in the discussion.
[2]This field lists the author(s) and the year of publication for each study. It provides information about who conducted the study and when it was published. It helps in identifying the source of the information and the timeframe in which the research was conducted.
[3]This field provides the name of the article, name and type of the model or framework proposed or analysed in each study. It helps to identify and differentiate between different models.
[4]The field outlines the main focus or objective of the model, such as assessing readiness for Industry 4.0, identifying key factors or dimensions, or proposing a new model. It helps in understanding the purpose and scope of the study.
[5]This field provides information about the main contributions or findings of the model. It helps in identifying the key insights or recommendations provided by the authors.
[6]This field lists the key dimensions, sub-dimensions, and indicators used in each readiness model to evaluate digital transformation readiness. It provides information about the specific factors considered important for smart execution. The levels field indicates the different levels of readiness defined in each model. It provides information about the progression or stages of readiness for I4.0 implementation. This field helps in understanding the structure and components of the models.
[7]This field provides a summary of the limitations or gaps identified in each model. It provides critical insight into the potential weaknesses or areas for improvement in each readiness model.
SME: Small and Medium-sized Enterprises

Table 3. Summary of Readiness Assessment Models

Figure 3 depicts a visual dispersion of readiness models produced by various countries across the globe highlighting the interest in developing economies about the I4.0 readiness.

Figure 3. Country Distribution

Table 3 presents a comprehensive overview of the reviewed readiness models (RM) including their corresponding industry types and size and main and sub-dimensions used. It indicates that small and medium companies were utilised more in readiness models as compared to large firms. It shows that the number of sub-dimensions varies widely across the dimensions, with some models having no sub-dimensions while others have as many as 60 sub-dimensions. For example, readiness models 3,5, 10-12 do not include sub-dimensions suggesting that these models do not delve into specific elements within the broad categories. On the other hand, readiness model 7 has 60 sub-dimensions which has a finer level analysis compared to other models in the graph. Furthermore, most readiness models have 5-7 dimensions and 10-40 sub-dimensions. The average count of dimensions and sub-dimensions across all models is approximately 5.95 and 18.7 respectively. This suggests that, on average, each readiness model addresses around 6 broad areas and 19 specific sub-dimensions within those areas.

4.2. The Integration of LM Concepts in the I4.0 Readiness Models

This section presents what LM concepts are integrated with I4.0 readiness models, RM1-RM20.

4.2.1. RM1: Organizational Readiness for Digital Innovation: Development and Empirical Calibration of a Construct (Lokuge et al., 2019)

While RM1 does not explicitly reference LM tools, several readiness dimensions align with lean concepts. For example, IT readiness echoes the lean concept of data-driven decision-making through its focus on leveraging data. Cultural readiness parallels employee engagement and leadership commitment, both essential for driving innovation. Innovation valence aligns with continuous improvement and process optimisation. The model emphasises resource readiness, which can involve minimising waste and optimising resource utilisation. It includes measures related to resource readiness and IT readiness, which can adopt automation technologies to boost efficiency and productivity. It measures cognitive readiness which can involve developing, offering Training and upskilling opportunities to employees. It also highlights measures related to strategic readiness, which can include leadership commitment to driving digital innovation. Moreover, it measures partnership readiness, which can involve fostering collaboration across different functions within the organisation. However, the model does not align with other lean concepts.

4.2.2. RM2: Industry 4.0 Readiness Assessment for South African Industries (Maisiri & van-Dyk, 2019)

RM2 does not explicitly integrate LM concepts but shares some overlaps. Organisational strategy aligns with lean's focus on process optimisation and continuous improvement culture, and the data-driven services dimension includes data-driven decision-making. The employee dimension could include lean concepts such as employee training and upskilling. The smart operations dimension includes automation and cross-functional collaboration. However, the model does not align with most of the other lean concepts.

4.2.3. RM3: The Degree of Readiness for the Implementation of Industry 4.0 (Pacchini et al., 2019)

Although RM3 is based on the SAE J4000 standard for lean performance, it does not explicitly incorporate LM tools. The model's technology enablers focus on improving readiness but lack direct reference to LM concepts outlined in Section 2.

4.2.4. RM4: Defining SMEs' 4.0 Readiness Indicators (Chonsawat & Sopadang, 2020)

Although RM4 does not explicitly integrate LM concepts, some elements can be inferred from the model's dimensions. The organisational resilience dimension, which focuses on business models and strategies, aligns with lean concepts like continuous improvement, leadership commitment, and supply chain management. Similarly, the manufacturing system dimension, encompassing industrial automation and collaborative robots, implicitly reflects automation and cross-functional collaboration. The infrastructure system dimension, which addresses infrastructure and standardisation, could also correspond with 5S methodology and standardisation. However, many key lean concepts are not explicitly addressed.

4.2.5. RM5: Developing an Industry 4.0 Readiness Model for Indian Engineering Industries (Sony & Aithal, 2020)

RM5 does not explicitly incorporate LM concepts but shares some parallels. The employee adaptability dimension reflects LM concepts such as training, upskilling, and adaptability- key to successful I4.0 implementation. The top management support dimension aligns with leadership commitment, essential for driving both lean and I4.0 initiatives. However other lean concepts are not addressed.

4.2.6. RM6: Digital Readiness Assessment of Italian SMEs: A Case-Study Research (Pirola et al., 2020)

Although RM6 does not explicitly mention LM concepts, several model dimensions align with lean concepts. The processes dimension reflects waste reduction, process optimisation, and continuous improvement culture. The people dimension ties into worker mindset, employee training and upskilling, and employee engagement. The strategy dimension could incorporate data-driven decision-making and leadership commitment, culture of adaptability, while the technology and integration dimensions might involve automation and cross-functional collaboration. However other lean concepts are not explicitly included.

4.2.7. RM7: Industry 4.0 Readiness Assessment: Comparison of Tools and Introduction of New Tool for SME (Axmann & Harmoko, 2020)

RM7 integrates several lean concepts, particularly in areas like data-driven decision-making through its focus on data storage, processing, data sharing, and quality. The categories of smart production, smart material planning, and smart maintenance align with lean tools such as JIT, Kanban, and TPM, emphasizing process optimisation and waste reduction. Automation is supported by the model's focus on machine readiness, IT security, and communication between machines, while continuous improvement and standardisation are core principles reflected in the model's structure. However other lean concepts are not explicitly covered.

4.2.8. RM8: Smart SMEs 4.0 Maturity Model to Evaluate the Readiness of SMEs Implementing Industry 4.0 (Chonsawat & Sopadang, 2021)

RM8 aligns strongly with LM tools and concepts. The Manufacturing and Operations dimension reflects lean concepts like process optimization, waste reduction, and automation. The people capability dimension ties into employee training, upskilling, and leadership commitment. Lean's culture of adaptability, lean supply chain, and cross-functional collaboration are represented in the model's business and organisation strategies dimension, which includes sub-dimensions like company culture and collaborative networks. The technology-driven processes dimension mirrors data-driven decision-making, while digital support aligns with visual management and standardisation. Although RM8 incorporates many lean concepts, it does not explicitly address worker mindset, employee engagement, 5S, JIT and Kanban, VSM, TPM, and quality management.

4.2.9. RM9: A Model for Assessing the Digital Transformation Readiness for Vietnamese SMEs (Hoa & Tuyen, 2021)

RM9 does not explicitly incorporate LM concepts but certain dimensions can be linked to lean. The productivity management dimension, which includes standards, aligns with lean concepts like process optimisation, waste reduction, and data-driven decision-making. The enterprise management dimension, covering leadership, customer orientation, and innovation culture, resonates with lean's focus on leadership commitment and continuous improvement. The SM dimension, which involves sensor systems and cloud-based databases, aligns with lean concepts such as automation and visual management. However, other core lean concepts are not explicitly addressed.

4.2.10. RM10: Conceptualizing Industry 4.0 Readiness Model Dimensions: An Exploratory Sequential Mixed-Method Study (Antony et al., 2023)

RM10 does not explicitly mention lean concepts, but several dimensions can align with them. For instance, employee adaptability reflects lean's focus on training, upskilling, and adaptability. The organisational culture and leadership support dimensions resonate with lean's emphasis on a culture of continuous improvement and leadership commitment. The digital transformation dimension ties into automation and data-driven decision-making, and the digitalisation of supply chains may correspond to lean supply chain management. However, the model does not directly address other lean concepts.

4.2.11. RM11: Design of A Business Readiness Model to Realise A Green Industry 4.0 Company (Benešová et al., 2021)

RM11 integrates several lean concepts, especially those aligned with green strategies. The model emphasizes waste reduction, a core aspect of LM, to support environmentally friendly practices. It also incorporates process optimisation and automation to enhance operational efficiency. The focus on employee training and upskilling reflects lean's commitment to building necessary competencies for I4.0 implementation, while leadership commitment is seen as essential for driving transformation. However, the model does not address a variety of other LM concepts making it less comprehensive in terms of overall lean integration.

4.2.12. RM12: Industry 4.0 Readiness of Technology Companies: A Pilot Study from Malaysia (Mansoor-Ahmed et al., 2021)

RM12 does not explicitly reference LM concepts, but certain overlaps can be observed. The model's focus on knowledge and competencies aligns with lean's emphasis on employee training and upskilling, while management support and motivation resonate with lean's leadership commitment and employee engagement. The model's focus on freedom to work on I4.0 technologies suggests a culture of adaptability, another Lean concept. However, the model does not address key LM concepts.

4.2.13. RM13: 3D-CUBE readiness model for Industry 4.0: Technological, Organizational, and Process Maturity Enablers (Felippes et al., 2022)

RM13 integrates several LM concepts across its three enabler dimensions. The organisational enablers dimension incorporates leadership commitment, employee training, and cross-functional collaboration, while the technological enablers dimension aligns with data-driven decision-making. The process maturity enablers dimension covers core lean concepts like process optimisation, waste reduction, continuous improvement culture, and supply chain and quality management. These concepts principles collectively enhance organisational readiness for I4.0 by promoting efficiency and improvement. However, it lacks explicit mention of other lean concepts.

4.2.14. RM14: Developing an Industry 4.0 Readiness Model Using Fuzzy Cognitive Maps Approach (Monshizadeh et al., 2023)

RM14 does not explicitly reference LM concepts, but certain elements align with lean. The operational readiness dimension resonates with process optimisation, while organisational readiness addresses continuous improvement culture, employee engagement, training, leadership commitment, and cross-functional collaboration. The technological readiness dimension, which includes digitalisation, cybersecurity, and smart supply chain, aligns with data-driven decision-making, automation, and lean supply chain concepts. However, other lean concepts are not explicitly covered.

4.2.15. RM15: Driving Factors of Industry 4.0 Readiness among Manufacturing SMEs in Malaysia (Annie-Pooi-Hang & Daisy-Mui-Hung, 2022)

RM15 does not explicitly incorporate lean concepts, but it highlights automation and employee training and upskilling as key aspects of technological readiness. Leadership commitment is also emphasised in the context of managerial preparation for I4.0. However, the model does not cover most of the other lean concepts.

4.2.16. RM16: Industry 4 0 Maturity and Readiness Assessment An Empirical Validation Using Confirmatory Composite Analysis (Hajoary et al., 2023)

RM16 integrates several lean concepts. It reflects waste reduction, process optimisation, and automation, while also emphasising data-driven decision-making and the need for employee training and upskilling. The model stresses leadership commitment, a culture of adaptability, and the importance of cross-functional collaboration in fostering I4.0 readiness. However, it does not explicitly mention other lean concepts.

4.2.17. RM17: A Framework to Measure Readiness and Barriers For The Implementation of Industry 4.0: A Case Approach (Govindan & Arampatzis, 2023)

While RM17 does not explicitly incorporate lean concepts, connections can be drawn. Data-driven decision-making is linked to business models, products, value chains, and operations, while employee training, upskilling, and cross-functional collaboration can be tied to the organisation and strategy dimension. Automation is associated with value chains and operations. However, the model does not cover many other lean concepts.

4.2.18. RM18: A Novel Model for Assessing the Degree of Intelligent Manufacturing Readiness in the Process Industry: Process-Industry Intelligent Manufacturing Readiness Index (PIMRI) (Zhao et al., 2023)

The PIMRI model does not explicitly integrate LM concepts, but lean parallels can be identified. The process dimension might include process optimisation, waste reduction, and continuous improvement culture, while the technology and intelligence dimensions could reflect automation and data-driven decision-making. The organisation dimension may involve employee training, leadership commitment, and cross-functional collaboration. However, other lean concepts are not explicitly discussed.

4.2.19. RM19: Assessment by Lean Modified Manufacturing Maturity Model for Industry 4.0: A Case Study of Pakistan's Manufacturing Sector (Sajjad et al., 2023)

RM19 incorporates data-driven decision-making and automation under smart operations and data-driven services dimensions. The importance of leadership commitment is noted in the I4.0 transformation process. The model aligns employee training and upskilling with the employee skill set dimension. Notably, the authors introduce a lean 4.0 dimension, though they do not explicitly address many other lean concepts in the proposed model.

4.2.20. RM20: Readiness Assessment for Smart Manufacturing System Implementation: Multiple Case of Indian Small and Medium Enterprises (Shukla & Shankar, 2023)

RM20 lacks explicit integration of lean concepts but includes data-driven decision-making, which aligns with the smart technology building block. The model's five readiness stages, including process building, could reflect lean's continuous improvement. Additionally, employee training and upskilling, leadership commitment, and culture of adaptability can be aligned with the people and SM awareness building block, while lean supply chain concepts relate to the supply chain management building block. However, detailed alignment with other lean concepts remains unclear.

4.3. Lean Manufacturing Concepts in Readiness Models

Even though explicitly not mentioned, the 20 readiness models (RM) presented encompass a variety of lean concepts that are integral to I4.0 initiatives (Table 4). As shown in Table 4, the most utilised lean concepts are leadership commitment, employee training and upskilling, automation, data-driven decision-making, process optimisation and continuous improvement culture, cross-functional collaboration, and waste reduction. However, the VSM process, one of the most frequently used lean concepts, is not mentioned in any of the readiness models (Table 4).

Employee training and upskilling is a recurring theme across the models, highlighting the role of human resources in lean implementation. Along with employee engagement, it will guarantee that staff have the essential skills and expertise to contribute effectively to the organisation's goals.

Readiness Model	Lean Concept																	
	Waste Reduction	Process Optimisation and Continuous Improvement	Data-driven Decision-Making	Worker Mindset	Employee Training and Upskilling	Employee Engagement	Leadership Commitment	Culture of Adaptability	Cross-Functional Collaboration	5S Methodology	Standardisation	Visual Management	JIT	VSM	TPM	Quality Management	Automation	Lean Supply Chain
RM1	x	x	x	x	x	x	x	x	x								x	
RM2		x	x		x				x								x	
RM3																		
RM4		x							x	x	x						x	x
RM5					x		x	x										
RM6	x	x	x	x	x	x	x	x	x								x	
RM7	x	x	x								x		x		x		x	
RM8	x	x	x		x		x	x	x		x	x					x	x
RM9	x	x	x				x				x	x					x	
RM10	x		x		x		x	x									x	x
RM11	x	x			x		x										x	
RM12					x	x	x	x										
RM13	x	x	x		x		x		x							x		x
RM14		x	x		x	x	x		x								x	x
RM15					x		x										x	
RM16	x	x	x		x		x	x	x								x	x
RM17			x		x				x								x	
RM18	x	x	x		x		x		x								x	
RM19			x		x		x										x	
RM20		x	x		x		x	x										x
Lean Usage	10	13	14	2	16	4	15	8	10	1	4	2	1	0	1	1	15	7

Table 4. Integration of Lean Concepts in Readiness Models

The culture of adaptability is another key concept, suggesting the necessity of flexibility and openness to change in a smart environment. Furthermore, the models underscore the significance of cross-functional collaboration for effective communication and coordination. It promotes communication and coordination across different departments, fostering an environment of teamwork. Some models incorporate specific lean methodologies such as

5S, JIT, Kanban, and TPM, demonstrating the application of structured approaches to waste reduction and process optimisation in achieving operational excellence.

Several models highlight the role of leadership and employee engagement, suggesting that commitment at all levels of the organisation is crucial for the successful implementation of I4.0 concepts and sustaining I4.0 initiatives. The models also suggest the use of standardisation, visual management, and continuous improvement culture to sustain the gains achieved through lean implementation. The inclusion of lean supply chain concepts and quality management in some models underscores the broad applicability of lean. These aspects will optimise the flow of materials and information, streamline processes, and reduce variability. In conclusion, these lean concepts are interrelated and mutually reinforcing, and they require a culture of adaptability, a positive mindset among workers and continuous improvement to be fully effective.

5. Discussion

Most of the readiness models have not integrated important lean concepts such as VSM, TPM, JIT, 5S, and Quality management, as a pre-requisite into the assessments of I4.0 readiness. Previous studies highlight that VSM is a useful tool for implementing I4.0 initiatives in manufacturing. VSM 4.0 is an extension of VSM that focuses on waste minimisation within a specific manufacturing process, considering data and information in the context of I4.0 (Bega et al., 2023; Lugert, Batz & Winkler, 2018; Sultan & Khodabandehloo, 2020). Further TPM is a valuable methodology for improving maintenance management and can be integrated with I4.0 technologies to achieve TPM excellence and improve maintenance processes (MaintWiz, 2023). JIT can be paired with I4.0 to create maximum efficiencies. The revitalization of the JIT philosophy can be combined with technologies made possible by I4.0 to develop a sourcing plan that excels in efficiency and agility (Henderson, 2023; Worximity, 2023). 5S methodology, in conjunction with other LM methodologies such as TPM and VSM can achieve operational excellence in an I4.0 environment (Picomto, 2020). Quality management is a critical aspect of I4.0, and the two concepts are closely related (Haleem, Javaid, Singh, Suman & Khan, 2023; Isolocity, 2023; Müller, 2019; Serour, 2023; Zaidin, Diah, Hui-Yee & Sorooshian, 2018). Quality 4.0 represents a rising concept in quality management within manufacturing industries, harnessing new technologies to enhance the implementation of quality management and organisational excellence (Oliveira, Rosa & Alvelos, 2022; Tulip, n.d.). Therefore, the lack of integration of VSM, TPM, JIT, 5S, and Quality management is a flaw in prevailing readiness models indicating the need for the requirement of a more complete readiness model for capitalising on existing capabilities in the digital transformation process.

5.1. Development of A Lean-Centric I4.0 Readiness Model

The limitations outlined in Table 3 reveal critical weaknesses in current I4.0 readiness models, such as limited sample sizes, overreliance on self-reported data, lack of external validation, absence of detailed subconstruct analysis, lack of lean concepts integrated and minimal integration of organisational and operational dimensions. These issues highlight the fragmented and often overly technology-focused nature of existing models. Recognising this, our study uses these gaps as a foundation to guide the development of a lean-centric I4.0 readiness model. Six new core dimensions were identified in the review as listed below in table 5. The refinement of these dimensions is achieved through the systematic classification of pre-identified LM concepts and dimensions mentioned in the 20 readiness models.

By integrating 39 sub-dimensions across six core readiness dimensions, our model offers a robust multidimensional framework (Figure 4). This lean-centric conceptual readiness model is designed to reflect the nuanced needs of manufacturing firms embarking on digital transformation. Each core dimension is subdivided into multiple sub-dimensions, enabling detailed and context-specific evaluation. While the development of individual assessment indicators is beyond the scope of this review, the model's architecture supports structured foundation. Each sub-dimension can be assessed using a 5-point Likert scale, ranging from 1 ("Not implemented") to 5 ("Fully implemented and integrated"). The cumulative scores across dimensions generate a readiness profile, enabling firms to identify their strengths and areas requiring improvement. This approach forms the basis of a maturity matrix, providing a practical method for firms to measure their readiness levels across technology, organisational, and process maturity enablers.

Core Dimension	Sub-dimension	Definition / Focus	Source(s)
Organisational Strategy and Leadership (6 sub-dimensions pooled) This core dimension focuses on strategic vision, leadership commitment, and organisational culture. It emphasises the pivotal role of leadership in aligning strategy with digital goals, fostering adaptability, and enabling collaboration across departments to drive successful I4.0 adoption.	Strategic Alignment & Enterprise Direction	Alignment of strategic goals, innovation culture, HR, and customer focus with I4.0 adoption objectives.	RM1, RM5. RM9
	Infrastructure & Organisational Capabilities	Availability of enabling resources (financial, physical, digital), systems, and structures for transformation.	RM2, RM13, RM15
	Workforce Competency & Adaptive Culture	Skills, cross-functional collaboration, employee empowerment, adaptability, freedom, and Lean-fostered agility.	RM3, RM4, RM12, RM13, lean concept
	Top Management Support & Leadership	Visionary, informed, and digitally literate leadership supporting I4.0 through strategy and decision-making.	RM5, RM10, RM11, RM15, lean concept
	Institutional Support	Government policies, incentives, and infrastructure aiding digital transformation efforts.	RM15
	Organisational Resilience	Internal communication, structural agility, and change-readiness within and across departments and partners.	RM4
Technology and Infrastructure (9 sub-dimensions pooled) This core dimension encompasses the foundational and advanced technological capabilities necessary for I4.0 implementation. It includes the readiness of IT systems, machine connectivity, data integration, and cybersecurity safeguards. Advanced technologies are integrated alongside Lean-enabled tools like automation and visual management to ensure real-time monitoring, seamless communication, and operational efficiency. These interconnected elements collectively support a scalable and resilient digital transformation in manufacturing environments.	IT and Technology Readiness	Basic digital infrastructure, including IT systems (ERP, mobile, cloud), interoperability, and foundational connectivity for digital operations.	RM1, RM10, RM12
	Digital Integration & Support	Digital support for operations across departments, integration of sensors and smart tools for real-time monitoring and decision-making.	RM5, RM8
	Advanced Technology Readiness	Readiness for adoption of smart, intelligent, and autonomous technologies such as AI, cobots, and autonomous systems that drive I4.0 capabilities.	RM3, RM13, RM16
	Machine Connectivity & Readiness	Sensorisation, machine-level communication (M2M), and IoT-enabled interoperability across manufacturing assets.	RM5, RM7
	Data Integration & Analytics	Capability for data collection, real-time access, big data analytics, and dashboarding to support predictive and prescriptive decision-making.	RM3, RM8
	Infrastructure & Digital Transformation Readiness	Adequacy of technical infrastructure (equipment, networks), financial commitment, and readiness to scale digital transformation.	RM4, RM9
	Advanced Manufacturing Technologies	Integration of cutting-edge production technologies such as additive manufacturing, digital twins, and cyber-physical systems for smart manufacturing.	RM3
	Cybersecurity & Data Protection	Preparedness to protect digital assets, systems, and communications through cybersecurity protocols, resilience measures, and risk mitigation practices.	RM4
	Visual & Automation Support Systems	Use of visual tools (digital dashboards, HMIs) and automation technologies to streamline operations and reduce human error.	lean concept

Core Dimension	Sub-dimension	Definition / Focus	Source(s)
Data Management and Processing (6 sub-dimensions pooled) This core dimension assesses the organisation's ability to harness data as a strategic asset across operations. It encompasses the integration and transformation of raw data into actionable insights, the maturity of storage and accessibility systems, and the effectiveness of data sharing within and beyond company boundaries. It also evaluates the quality and standardisation of data, legal and cybersecurity safeguards, and the cultivation of a data-driven culture that enables new services and informed decision-making. Lean and I4.0 principles are embedded to promote efficient, real-time, and value-generating use of data across the enterprise.	Data Integration & Transformation	Converting raw data into actionable insights using real-time acquisition, cloud platforms, and analytics.	RM4, RM7
	Data Storage & Accessibility	Maturity of secure, centralised, and scalable data storage infrastructure, enabling informed decision-making.	RM7
	Data Sharing & Interoperability	Capacity for seamless, real-time data exchange across internal systems and external partners.	RM7
	Data Quality & Processing Maturity	Ensuring data accuracy and optimisation through formatting, automation, and KPI-based evaluation.	RM7
	Legal, Security & Governance	Protection of digital assets through IP, cybersecurity, and compliance frameworks.	RM17
	Data-Driven Culture & Services	Leveraging data for real-time decisions, service innovation, and customer-focused business models	RM2, RM19, Lean concept
Operations and Processes (6 sub-dimensions pooled) This core dimension focuses on enhancing operational efficiency through the integration of digital technologies and lean concepts It encompasses smart, data-driven manufacturing and logistics systems, supported by foundational tools such as 5S, JIT, standardisation, and process optimisation. The goal is to streamline workflows, reduce waste, improve quality, and ensure readiness for scalable, real-time, and adaptive I4.0 operations.	Integrated Smart Manufacturing	Digitally integrated, responsive, and automated production and maintenance systems.	RM7, RM8, RM16, RM20
	Smart Supply Chain Planning & Logistics	Digital coordination of material planning and logistics using automation, KPIs, and real-time tools.	RM7
	Smart Products and Services	Intelligent, connected products and services with embedded sensors and real-time feedback.	RM10
	Digital Business Process Excellence	Digitised, monitored, and optimised processes supporting efficiency, agility, and sustainability.	RM9,11,13
	Lean-Enabling Practices for I4.0	Foundational Lean tools ensuring waste-free, standardised, and digital-ready operations.	lean concept
	Smart Operations	Horizontal and vertical integration of value chains enabled by cloud, automation, and cybersecurity.	RM2,19

Core Dimension	Sub-dimension	Definition / Focus	Source(s)
People and Culture (8 sub-dimensions pooled) This core dimension focuses on the human and organisational capabilities essential for successful Industry 4.0 transformation. It emphasises the development of a skilled, adaptable, and motivated workforce supported by strong leadership, a culture of continuous improvement, and a readiness to collaborate and take calculated risks. Drawing from lean concepts, it underscores the importance of employee engagement, cognitive preparedness, and structured reward systems to drive innovation. A supportive organisational culture that fosters idea sharing, learning, and decentralised decision-making is critical to enabling sustained digital evolution.	Employee Skills and Adaptability	Readiness and capability of employees to develop and apply both hard (e.g., automation, analytics) and soft (e.g., problem-solving, adaptability) skills required for I4.0 transformation.	RM5, RM10 RM19, lean concept
	Employee Engagement and Motivation	Degree to which employees are actively involved, motivated, and aligned with organisational goals, playing a vital role in successful digital transformation and continuous improvement.	RM12, lean concept
	Leadership and Talent Awareness	Extent to which leaders and the workforce are aware, competent, and prepared to drive and support Smart Manufacturing initiatives.	RM20
	Reward and Recognition Systems	Structured incentives and recognition mechanisms that encourage and reinforce desired behaviours and contributions toward Industry 4.0 initiatives.	RM10
	Cultural and Organisational Readiness	Presence of a supportive organisational culture that encourages innovation, risk-taking, decentralised decision-making, and collaboration for digital transformation.	RM1, RM10, RM12
	Continuous Improvement Orientation	A mindset across all levels of the organisation focused on ongoing enhancements in processes and systems, critical for adapting to evolving Industry 4.0 demands.	lean concept
	Collaborative Readiness	Preparedness of people to engage in cross-boundary partnerships and co-innovation with suppliers, customers, consultants, and technology partners.	RM1
	Cognitive Readiness	Psychological and intellectual preparedness of employees to absorb, comprehend, and respond to technological change and digital innovation.	RM1
Supply Chain and Market Factors (4 sub-dimensions pooled) This core dimension assesses the extent to which firms leverage digital technologies and lean concepts to enhance supply chain performance and respond effectively to evolving market demands. It encompasses the digitalisation and end-to-end integration of supply chains, the application of lean practices to streamline processes, the strategic influence of market dynamics and perceived advantages driving I4.0 adoption, and the use of digital tools in marketing and sales to strengthen customer engagement and competitiveness.	Digitalised Supply Chain	Degree of real-time, smart technology integration and visibility across supply chain processes.	RM5, RM10, RM16
	Lean Supply Chain	Application of lean concepts to streamline and synchronise supply chain operations.	lean concept
	Market Responsiveness and Strategic Motivation	Influence of market dynamics, perceived benefits, and competitive pressure on I4.0 adoption.	RM12, RM15
	Digital Marketing and Sales	Adoption of digital tools for marketing, sales, and customer interaction strategies.	RM17

Table 5. Lean-centric Readiness Model Dimensions

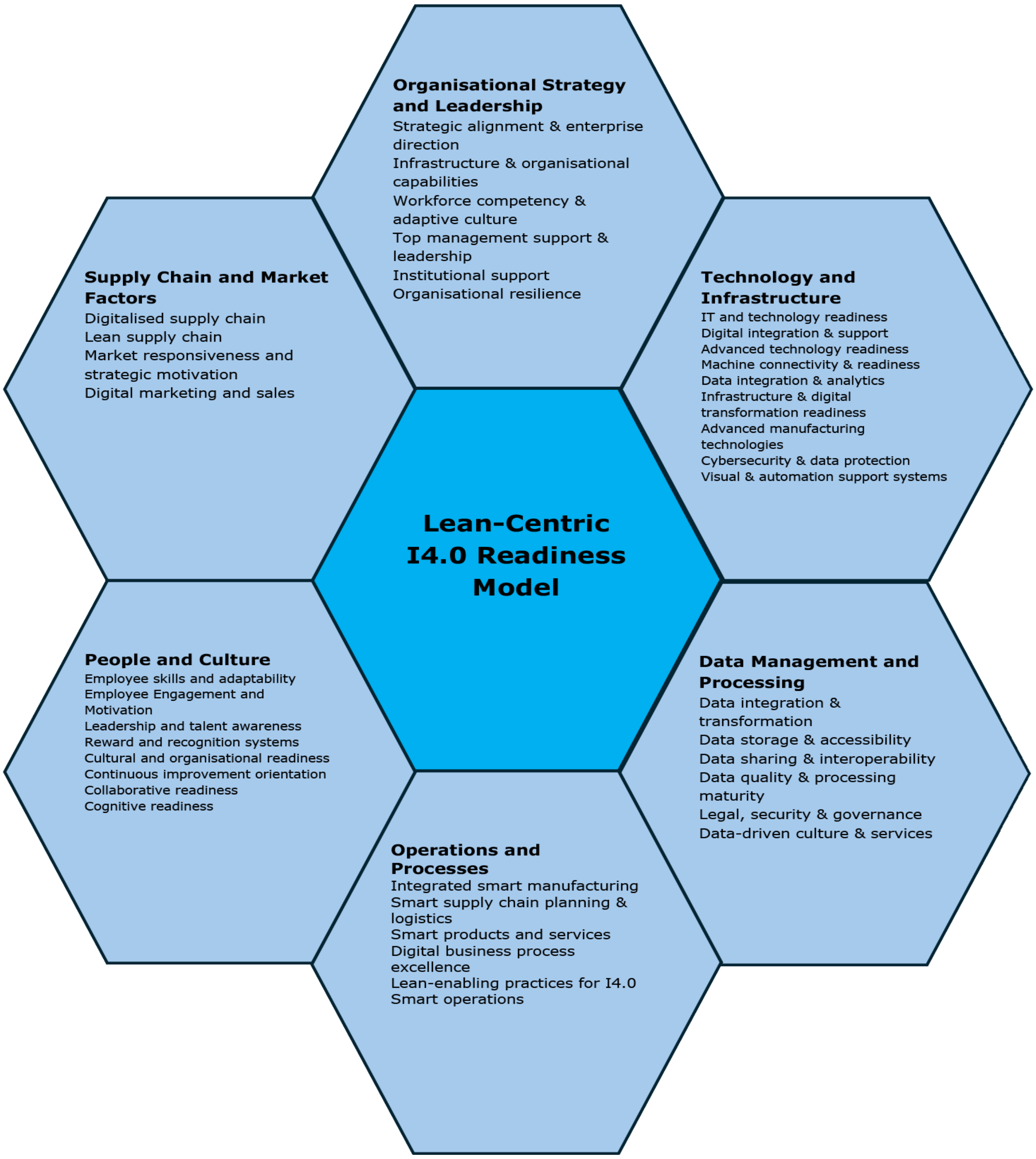

Figure 4. Lean-centric Conceptual Readiness Model

The inclusion of LM concepts often neglected in existing models ensures both theoretical rigour and practical relevance. By embedding LM concepts within the sub-dimensions, the model not only aligns with lean practices but also enhances firms' capacity for a seamless I4.0 transition. Moreover, the knowledge extracted from prior model limitations directly informed the structure, scope, and application strategy of this model, offering firms a diagnostic roadmap to benchmark performance, identify gaps, and plan targeted improvements for sustainable digital transformation.

6. Conclusion and Implications

This study investigated how lean concepts are being used in the existing I4.0 readiness models using the SLR method. It reviewed 20 existing I4.0 readiness models to investigate the interplay between lean concepts and the dimensions of readiness models. The findings identify a significant void, as most of the essential lean concepts have not been integrated into the assessments of I4.0 readiness. VSM, TPM, JIT, 5S, and quality management are found to have the least presence in existing readiness models. Through a systematic classification, a novel conceptual readiness model centred on lean concepts for I4.0 is proposed.

The proposed novel lean-centric I4.0 readiness model comprises six core dimensions and 39 sub-dimensions and extends the previous 20 readiness studies by addressing their limitations and providing a more comprehensive and practical approach to integrating lean capabilities into I4.0 technology adoption. It aligns with previous studies on the importance of technology, organisational, and process maturity enablers in achieving I4.0 readiness (Ansari et al., 2023; Felippes et al., 2022; Schumacher et al., 2016). It extends previous studies by embracing the essential lean concepts into the proposed model. It contradicts previous studies that suggest that technology is the most vital dimension among the present I4.0 readiness models (Hizam-Hanafiah et al., 2020) and emphasises the equal importance of technology, organisational, and process maturity enablers of I4.0 readiness.

6.1. Theoretical and Practical Implications

This study holds both theoretical and practical significance. Previous I4.0 readiness models did not emphasise the inclusion of lean implementation as an input dimension (Hizam-Hanafiah, Soomro, Abdullah & Jusoh, 2021; Pacchini et al., 2019). The proposed novel lean-centric readiness model describes the relationships between the readiness model dimensions investigated in this review and is supported by the extant literature findings. It paves the way for a novel perspective, prompting researchers to consider the incorporation of lean concepts as integral readiness parameters. Furthermore, it facilitates the comprehensive evaluation of organisational readiness, encompassing both tangible, such as resources, and less tangible, such as cultural factors dimensions (Lokuge et al., 2019). This underscores the significance and the necessity of addressing pertinent factors before embarking on a digital transformation journey (Aras & Büyüközkan, 2023; Wongsunopparat and De-Silva, 2023; Trenerry, Chng, Wang, Suhaila, Lim, Lu et al., 2021).

From a practical perspective, this research offers valuable support to leaders and practitioners in manufacturing firms, aiding them in gaining a deeper understanding of the significance of lean implementation before embarking on the incorporation of I4.0 technologies within their organisations (Buer et al., 2018; Ejsmont et al., 2020; Sony, 2018). The application of the proposed model will potentiate the decision-making process and strategy formulation (Sajjad et al., 2023), thereby avoiding the occurrence of "false starts" that have, in the past, contributed to the notably high rate of innovation failures (Lokuge et al., 2019). Furthermore, this study serves as a guiding tool for understanding the essential readiness dimensions that necessitate consideration before the implementation of I4.0.

For managers, the model serves as a valuable instrument for assessing the current state of the organisation, enabling them to rationalise and strategize improvements. Simultaneously, it empowers managers to determine their priorities and overcome barriers obstructing the seamless integration of I4.0 (Govindan & Arampatzis, 2023). Having understood, standardised, and spotted possible fields of strength and weakness concerning readiness for digital transformation, the organisations are better equipped to allocate resources based on empirical evidence (Lokuge et al., 2019). Additionally, organisations should leverage these results to disseminate best practices and learnings throughout their supply chain network (Aniruddha-Anil, Joshi, Ajay-Pal-Singh & Jain, 2021). The result of the study provides practical guidelines for the formulation of a robust I4.0 implementation strategy that aligns seamlessly with their overarching business strategy (Aniruddha-Anil et al., 2021). Lastly, leveraging the readiness result will lead to the execution of a comprehensive and all-encompassing approach to I4.0.

7. Limitations and Future Work

In terms of study limitations, it is essential to acknowledge several factors that may affect the comprehensiveness and scope of this review. Firstly, the review was conducted solely as a literature review, without the inclusion of primary data collection. Consequently, the findings are reliant on historical data, providing a snapshot of the state at a specific point in time. The review was confined to English-language publications, potentially excluding relevant research on I4.0 readiness models published in other languages. Also, the search for relevant literature was conducted using specific databases and predefined keywords, as detailed in the methodology section. Given the continuous expansion and updates of research repositories and databases, it is plausible that some relevant literature may not have been included in this study.

The review is based on the published literature on manufacturing where LM practices may have different degrees of adoption in different manufacturing sectors. Although the study primarily concentrates on the manufacturing sector, its findings hold an opportunity to extend the outcomes of this research to other industries, thereby enriching our understanding of readiness for the digital era. Subsequent researchers are encouraged to devise pertinent indicators for the assessment of the model and create a maturity matrix grounded in the dimensions established through this research. Moreover, they are empowered to formulate transformation strategies guided by the readiness scores.

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