Available online at : http://josi.ft.unand.ac.id/

Jurnal Optimasi Sistem Industri

| ISSN (Print) 2088-4842 | ISSN (Online) 2442-8795 |

Research Article

Developing an Industry-Specific Lean 4.0 Readiness Assessment Tool: A Case for the Chemical Sector

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DOI: 10.25077/josi.v23.n2.p283-298.2024 **Submitted** : August 15, 2024; **Accepted** : December 21, 2024; **Published** : January 30, 2025

ABSTRACT

In an era where digital transformation is increasingly imperative, many industries struggle to navigate the complexities of technological adoption and operational efficiency. Lean principles, which emphasize waste reduction and process optimization, provide a robust foundation for digital transformation, particularly in the chemical industry, where unique operational challenges exist. This research aims to develop an integrated Lean 4.0 readiness assessment tool to bridge the gap between leanness and Industry 4.0 readiness. The study begins with a literature review on existing lean and Industry 4.0 readiness measurement tools and integrates them to create a new framework, using the Indonesia Industry 4.0 Readiness Index (INDI 4.0) as a reference, tailored specifically to the chemical industry. Expert interviews are conducted to refine the assessment tool, ensuring alignment with real-world industry conditions and practical insights. A Delphi-based expert consensus method combined with a fuzzy approach for handling imprecision in indicator ratings is employed to validate the framework, resulting in five key dimensions and 86 indicators. By gathering expert input, the tool addresses the chemical industry's specific challenges and simplifies readiness evaluation, helping companies assess their preparedness for digital transformation and identify areas for improvement. The resulting framework enables chemical companies to bridge readiness gaps and prioritize targeted enhancements. Furthermore, this tool has the potential to serve as a scalable model for other industries, fostering more efficient and strategic digital transformation aligned with Industry 4.0 objectives globally.

Keywords: Digital Transformation, Lean 4.0 readiness assessment, fuzzy-Delphi approach, chemical industry

INTRODUCTION

Manufacturing industries typically operate within a highly competitive environment, where new difficulties continually arise, including the emergence of disruptive concepts and technologies [1],[2]. Manufacturers must maintain elevated standards of quality, productivity, and cost-effectiveness. Companies must agile, efficient, and responsiveness to evolving customer demands, along with an emphasis on product quality and regulatory compliance, are critical for the survival [3]. To tackle the identified challenges and adapt to evolving customer demands in competitive landscapes, manufacturing strategies and processes must be flexible [4], significantly reduce operational costs, and possess the capability to operate intelligently and autonomously [5],[6]. This necessitates a significant degree of digitalization and automation, along with comprehensive connection inside manufacturing settings and across enterprises, hence demanding the seamless integration of production systems, machinery, and enterprise systems [7]. Furthermore, organizations must possess the ability to swiftly respond to increasing market demands [8]. Consequently, various methodologies, like Lean Manufacturing and, more recently, Industry 4.0 (I4.0), have been formulated to assist industries in attaining these objectives.

Among manufacturing industries, the chemical industry is a very broad industry that involves converting various basic materials such as oil, natural gas, air, water, metals, and minerals into a wide range of over 70,000 distinct products [9]. This industry involves chemical processes that produce new substances through chemical reactions, based on their special properties such as solubility, temperature, equilibrium, heat effects, and other attributes. The chemical industry is concerned with the processing of unrefined resources acquired from mining, agriculture, and other origins, into products that can be used in other industries or as end products intended for public consumption [10],[11]. The chemical industry is significantly dependent on continuous production and batch processing, in contrast to discrete manufacturing (e.g., automotive or electronics). Operational stability, efficiency, and waste minimization are critical due to the emphasis on material transformations through chemical reactions.

Manufacturing companies play a vital role in advancing the Sustainable Development Goals (SDGs) by emphasizing sustainable product development, optimizing resource efficiency, and investing in renewable energy infrastructure [12], [13]. As part of its commitment to sustainable development, Indonesia has integrated SDG targets into its national development plans and priorities [14]. Industry 4.0 (I4.0), primarily associated with economic growth and productivity, aligns with SDG 8 (decent work and economic growth) and SDG 9 (industry, innovation, and infrastructure) [15]. It represents the latest industrial revolution, driven by digital technology and automation, fundamentally reshaping how organizations operate. Recognizing its significance, the Indonesian Ministry of Industry has developed the I4.0 Roadmap to guide the country's industrial transformation [16]. The term Industrie 4.0 broadly refers to the transition of organizations toward digitalization, with a strong emphasis on integrating Cyber-Physical Systems (CPS) within industrial processes and leveraging Internet of Things (IoT) technology to enhance efficiency and connectivity in manufacturing [17].

The implementation of the I4.0 concept requires the integration of several technologies. According to [18], nine main technologies are the foundation of the I4.0 concept, namely the Internet of Things (IoT), cloud services, cybersecurity, additive manufacturing (AM), Augmented Reality (AR), Big data & Analytics, Autonomous robots, Simulation (digital twin), and Integration of horizontal and vertical systems. In addition, the business environments and customer requirements also evolve with the new form of digitalization in the organization. The primary attribute of I4.0 is the utilization of cyber-physical systems in production (CPS), these systems have a significant role in achieving the agile and dynamic requirements of production [19]. Lean 4.0 is essential for attaining operational excellence, improving sustainability, and tackling the specific issues of the chemical sector, where continuous processes can rapidly result in substantial waste due to inefficiencies. Minor fluctuations in temperature or pressure may result in product defects or inefficiencies, which can be alleviated by employing IoT and advanced sensor-connected devices to monitor equipment and process parameters in real time. Digital twins are also being widely implemented. Digital twins facilitate real-time process optimization, predictive analysis, and hypothetical scenario testing by generating a virtual counterpart of the chemical plant, thereby minimizing waste and enhancing flow.

In the past, manufacturing solely involved a sequence of procedures to transform raw materials into final products. However, today it considers data-driven business operations that lead to Smart Manufacturing [20]. By implementing I4.0, manufacturing companies can increase productivity, respond to the market faster, and compete globally [21]. Digital technologies can increase the flexibility of products and services with the support of continuous evolution [22] and enable real time data analysis, decision making, and product development [23].

The implementation of I4.0 requires readiness among all elements in a company's ecosystem. This includes preparing employees with new skills, developing advanced technology infrastructure, and transforming business processes to be more efficient [24]. But is implementing I4.0 easy? The reality is that around 70% of companies have failed in

DOI:10.25077/josi.v23.n2.p283-298.2024

Figure 1. Approach to Lean and Digital Production Systems

digital transformation [25], getting off track and not getting the benefits as planned [26]. Success in adopting I4.0 is not only a technological change, but also an underlying cultural and mindset change throughout the organization. Adoption must also involve the related supply chain, to be aligned and comprehensive. Thus, an assessment tool is needed that can measure the level of readiness of the company to implement I4.0.

Lean manufacturing involves the use of tools and techniques to ensure that manufacturing processes add value to customers, flow smoothly through the supply chain, eliminate waste, defect and process variation for improving quality and productivity [27],[28]. Lean encourages long-term supplier relationships to ensure consistency in material quality and delivery schedules, which is crucial for chemical processes that require precise input specifications. In contrast to discrete industries, waste in the chemical sector encompasses not only inventory and downtime but also energy losses, byproducts, emissions, and hazardous waste, all necessitating specific management. Waiting is typically regarded as waste; nonetheless, in the process sector, it becomes inevitable due to the set time requirements of chemical processes (e.g., curing, fermentation), which constrain the potential for enhancing process speed [29]. Lean is the basis for the application of I4.0, so not implementing lean principles can have serious consequences [30]. When I4.0 technology is applied to inefficient processes, waste can increase, if not implemented with a focus on sustainability and efficiency management. Careful planning and integration of these technologies are crucial to maximize their advantages while mitigating potential adverse effects on waste production. For example, if a production line has poor material flow or bottlenecks, automation may increase throughput at one stage but worsen delays or errors in downstream processes. According to [31], there are several stages from lean to I4.0 as shown in Figure 1.

Depending on main goals, previous researchers have developed various maturity models, but in separate tools, either LAT (Lean Assessment Tools) or Industry 4.0 Readiness index, as shown in Table 1. The literature review indicates that existing forms of assessment operate independently and lack interconnection [32]. Lean Assessment Tool (LAT) is only used for lean assessment, such as Brito et al. [33], Harjanto and Daingsih [34], Muhammad and Kisih [35], and Lyon [36], who develop LAT for several industries and services. As mentioned in figure 1, evaluating the maturity and level of lean and digital, and implementing lean is a prerequisite for successful digitalization, thus the integration of both LAT Lean and I4.0 will be more practical and more targeted. Especially the chemical industry (process industry) which has different characteristics from the discrete industry, such as the just-in-time method which is less suitable for the chemical industry that has a complex supply chain. This is why the creation of integrated LAT is very much needed. The LAT consists of several dimensions and indicators to allow researchers or practitioners to do assessment and obtain maturity level of lean implementation. Unfortunately, articles about LAT in Chemical Industries are very rare, there were any LAT research, but more than 10 years passed, as mentioned by Lyon [36] and Lyu et al. [37.

Meanwhile, with the emerging of digital transformation, some IR 4.0 assessment tools have been developed, such as An Industry 4.0 Readiness Assessment Tool, VDMA IMPULS - Industry 4.0 Readiness [31], Industry 4.0/Digital Operations PwC Self-Assessment [32], Singapore Smart Industry Readiness Index (SIRI 4.0) [33], and Indonesia Industry 4.0 Readiness Index (INDI 4.0) [34]. They provide guidance to companies about the level of readiness for

Table 1. State of the Art and Research Gap

No.	Tool(s)	Content			Sector			
		Lean	LAT	IR 4.0	Service	SME	Manufacture Discrete	Process/Chemical Industry
1.	Alarcon	√						√
2.	Muganyi	√						√
3.	Demchuk	√						√
4.	Belhadi	√						√
5.	Lyons et al. [36]		√					√
6.	Idanha [27]	√						√
7.	King and King [39]	√						√
8.	Lyu et al. [37]		√					√
9.	VDMA IMPULS [40]			√			√	
10.	University of Warwick			√			√	
11.	Omogbai & Salonitis		√				√	
12.	EDB of Singapore [41]			√			√	
13.	Kemenperin RI [42]			√			√	
14.	PriceWaterhouseCoopers (PwC)[43]			√			√	
15.	Brito et al. [33]		√				√	
16.	Muhammad and Kisih [35]		√		√			
17.	Harjanto and Daingsih [34]		√			√		
18.	Rahmatindar et al. [38]		√	√			√	
19.	Proposed research		√	√				√

carrying out digital transformation. The companies will know their position and its weak points, and it would be such guidance for transformation.

According to Heilthaler [31], Lean is fundamental for implementation I4.0, when implementing I4.0 without practicing lean principles can have serious consequences, so integration between Lean and I4.0 are mandatory, namely Lean 4.0 [38]. Lean 4.0 Readiness Assessment Tool can be used to measure level of lean implementation (leanness level) and the readiness level of Industry 4.0. However, according to Rahmatindar et al. [38] who develop those integration assessment tools for generic manufacturing industry.

The chemical industry has its own specific characteristics. Chemical industry is known as process industry or continuous process, involving a continuous flow of material through various processing equipment, involving chemical reactions and the product is measurable & undistinguishable [36]. It is diferent with discrete processes, like automotive and electronic industry, that makes a difference in term of lean manufacturing implementation [27]. For example, the elimination of waiting and the implementation of JIT would be highly risky in the chemical industry, where waiting times can be intrinsic, such as chemical reaction times, fermentation processes, or cooling/heating times. This waste is difficult to eliminate because it is part of the process characteristics. Moreover, process industries often have production facilities designed for continuous operation, making the just-in-time system less suitable for the sudden changes that frequently occur in JIT systems.

Building on these challenges, this research addresses a critical gap in existing readiness assessment tools by developing an integrated Lean 4.0 readiness tool specifically tailored for the chemical industry. Unlike previous

DOI:10.25077/josi.v23.n2.p283-298.2024

frameworks that treated lean assessment and Industry 4.0 readiness separately, this study combines both aspects into a unified evaluation model. The proposed tool not only provides companies with a structured approach to assessing their current Lean 4.0 readiness but also guides them in making informed decisions for implementing digital transformation effectively. This study is particularly significant as it introduces a comprehensive assessment instrument capable of analyzing multiple dimensions simultaneously, encompassing lean manufacturing, Industry 4.0, and the unique characteristics of the chemical sector.

METHODS

Numerous studies have explored the implementation of lean principles in the manufacturing sector; however, no existing assessment instrument specifically evaluates the leanness level of the chemical industry. This study aims to bridge this gap by developing a dedicated lean assessment instrument tailored to the unique characteristics of the chemical industry. The development of indicators for assessing leanness in the chemical sector differs slightly from those applied in manufacturing and service industries due to the distinct nature of chemical processes compared to discrete industries, as discussed in the previous chapter.

The development of the Lean Assessment Tool (LAT) follows a structured five-stage process. The first stage involves the identification phase, conducted through a comprehensive literature review spanning the past decade. This review covers key topics, including the chemical industry, lean manufacturing, Industry 4.0, Industry 4.0 Readiness Assessment Tools, Lean Assessment Tools, the Delphi Method, Triangular Fuzzy Number, and the Analytical Hierarchy Process (AHP). A systematic literature review, supported by previous research [44],[45], alongside bibliometric analysis using Google Scholar, Scopus databases, and VOSviewer software, is employed to identify relationships among relevant articles. This literature review is essential for understanding the research context, guiding the research design and methodology, and constructing a robust theoretical framework. Additionally, it helps identify gaps in existing research, such as the limited application of lean principles in continuous manufacturing processes, thereby contributing novelty and relevance to the current study.

The second stage focuses on determining assessment dimensions and indicators. This step is crucial in developing a new model that integrates Industry 4.0 readiness, LAT, and the distinct characteristics of process-based (chemical) industries. To refine the questionnaire, several established assessment models are referenced, including WMG - An Industry 4.0 Readiness Assessment Tool, VDMA IMPULS - Industry 4.0 Readiness [40], INDI 4.0 [42], Industry 4.0/Digital Operations PwC Self-Assessment [43], and the Singapore Smart Industry Readiness Index [24],[41]. Furthermore, insights from LAT models [33],[34] and process industry characteristics [36],[27],[39] are incorporated to ensure the assessment tool is well-aligned with the specific needs of the chemical industry.

The third stage involves data collection, which is conducted through a questionnaire distributed to experts in the chemical industry with expertise in Lean and Industry 4.0 implementation. Experts review and provide feedback on the proposed dimensions and indicators using the Delphi method. The outcome of this stage is the establishment of consensus on the most appropriate dimensions and indicators, as well as the evaluation of their relative importance. This step is essential for validating the LAT draft from a practitioner's perspective, ensuring that the framework consolidates insights from the literature with real-world industry conditions. Additionally, since this research explores a relatively new field within the chemical sector—an area that has received limited attention in prior studies—expert feedback is crucial to ensure the tool's applicability, universality, and alignment with the latest industrial developments.

The fourth stage involves data processing, where responses from the questionnaires are compiled and analyzed. The data is processed using triangular fuzzy numbers, which measure the gap between the value of each triangular fuzzy

Scale	Linguistic definition	Fuzzy Number
1	Completely Not important	(0, 0, 0.25)
2	Not important	(0, 0.25, 0.5)
3	Ordinary	(0.25, 0.5, 0.75)
4	Important	(0.5, 0.75, 1)
5	Very important	(0.75, 1, 1)

number and the average triangular fuzzy number. The Delphi method is conducted in two rounds. In the first round, experts provide their opinions on the appropriateness of the proposed indicators derived from the literature review, specifically within the context of the chemical industry. Additionally, they can suggest new indicators that may be relevant to the existing dimensions and indicators. The second round of the Delphi method requires experts to assess the importance of each indicator using a five-point Likert scale, ranging from "very unimportant" to "very important." These assessments are then transformed into fuzzy numbers, with triangular fuzzy numbers employed for quantifying expert judgments. The conversion of Likert scale values into fuzzy numbers follows the reference values presented in Table 2. Finally, the fuzzy numbers are analyzed to determine whether a consensus has been reached regarding the dimensions and indicators.

Furthermore, defuzzification is essential to refine the assessment process by converting fuzzy scale values into precise crisp values, ensuring a more accurate evaluation of each indicator. This transformation eliminates ambiguity and enhances decision-making in determining indicator validity. An indicator is considered valid and applicable for assessment if its crisp value meets or exceeds 70%, as outlined by Pandor et al. [46]. This process enhances the reliability of the Lean 4.0 readiness assessment by ensuring that only the most relevant and industry-aligned indicators are incorporated into the final model.

The fifth stage focuses on establishing a structured Industry 4.0 readiness measurement framework tailored specifically for the chemical industry, as detailed in Table 3. This framework categorizes companies into five levels of readiness, providing a systematic approach to evaluating their maturity in adopting Lean 4.0 principles. The readiness level is determined based on the percentage of fulfillment of each indicator within the Lean 4.0 Assessment (LAT) framework. This classification system not only enables organizations to identify their current status in the Lean 4.0 transformation journey but also assists in recognizing specific gaps that require targeted improvement strategies. By utilizing this structured assessment, companies can develop well-informed action plans to enhance their preparedness for digital transformation. Moreover, this readiness framework serves as a practical guideline for industry practitioners, policymakers, and decision-makers in designing and implementing structured preparation programs that align with their Lean 4.0 adoption goals.

To gain deeper insights into the adoption level of Industry 4.0 across various dimensions, value mapping using radar plots is employed as a powerful visualization technique. Radar plots provide a comprehensive and intuitive

Table 3. Criteria of lean 4.0 readiness level

Level	Percentage fulfillment each indicators	Readiness criteria
0	0 – 20%	company Not Ready to implement Lean 4.0
1	20% - 40%	company in Early stages of Lean 4.0 implementation
2	40% - 60%	company in Intermediate stages of Lean 4.0 implementation
3	60% - 80%	company in Advance of Lean 4.0 implementation
4	80% - 100%	company Already implemented Lean 4.0

DOI:10.25077/josi.v23.n2.p283-298.2024

representation of a company's Industry 4.0 readiness by simultaneously displaying multiple dimensions in a single graphical output. These plots are widely recognized for their effectiveness in multivariate data analysis, particularly in benchmarking applications where multiple performance metrics need to be compared [47]. By leveraging radar plots, organizations can identify strengths, weaknesses, and opportunities for improvement in their digital transformation strategies. Furthermore, these visual tools facilitate comparative analysis between different companies or business units, allowing for a more strategic and data-driven approach to Industry 4.0 implementation [48]. The ability to distill complex data into an easily interpretable format makes radar plots an indispensable tool for guiding organizations toward achieving a higher level of Industry 4.0 maturity.

RESULT AND DISCUSSION

In the identification stage, a literature review and bibliometric analysis were conducted to explore existing research related to the Lean 4.0 Readiness Assessment Tool. Bibliometric analysis was supported by the Google Scholar database, which provided access to 4,415 journal articles published in the past 10 years, and VOSviewer software (version 1.6.19), which facilitated network visualization and article clustering, as illustrated in Figure 2. The keywords used for the search included "Lean Assessment Tool," "Industry 4.0 Readiness Assessment Tool," and "Lean in Process Industry." The visualization results indicate a significant research gap in Lean 4.0 readiness within the process industry, showing a weak correlation between lean manufacturing and process industries. While 43 papers were identified using the specified keywords, fewer than 15 articles explicitly addressed assessment tools, highlighting a lack of research and significant opportunities for further exploration in this domain.

The determination of dimensions and indicators is based on the reference model INDI 4.0, developed by the Indonesian Ministry of Industry, as detailed in Appendix A1. INDI 4.0 consists of five dimensions and 17 indicators. This model was modified by integrating indicators from previous studies on the Lean Assessment Tool (LAT),

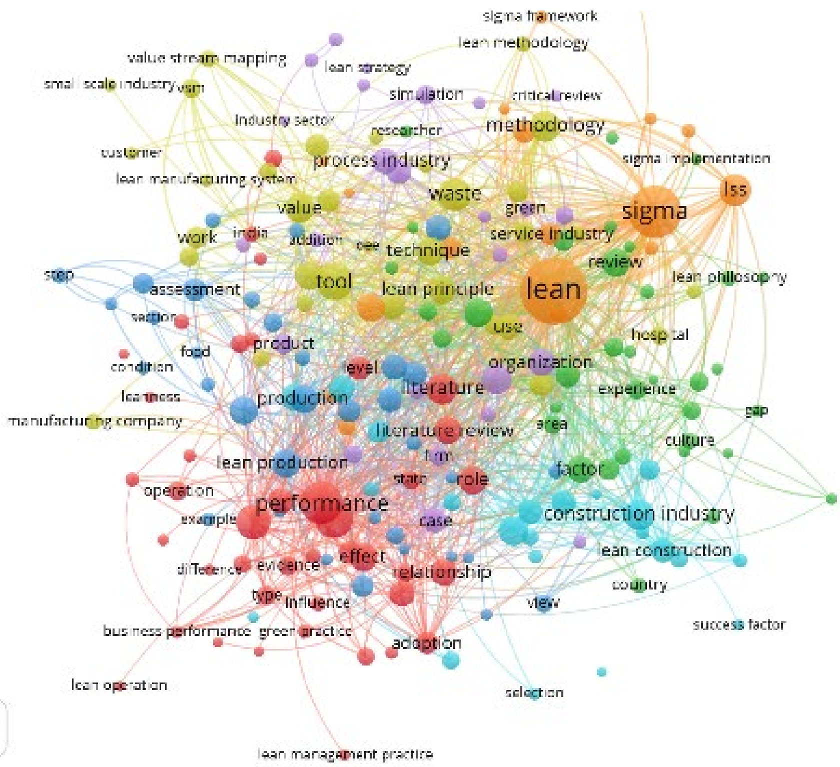

Figure 2. Network visualization and clustering of documents

selected based on their potential for integration due to keyword similarities and indicator characteristics. Five key LAT studies referenced in this research include those by Lyon [36], Boamah et al. [49], Brito et al. [33], Muhammad and Kisih [35], and Harjanto and Daingsih [34]. The detailed dimensions for each LAT model are presented in Appendix A2.

The five dimensions used in this study align with INDI 4.0, namely management and organization, people and culture, products and services, technology, and plant operations. A synthesis was conducted by integrating insights from existing literature on Industry 4.0 readiness assessments and lean assessment tools, covering various industry sectors, including discrete manufacturing, process manufacturing, service industries, and small and medium-sized enterprises (SMEs). INDI 4.0 was selected as the primary reference due to its comprehensive coverage of relevant assessment criteria. Following this, an alignment analysis was performed with previous LAT models, leading to the development of the Lean 4.0 Readiness Assessment Tool. The final proposed Lean 4.0 Assessment Tool consists of five dimensions and 157 indicators, providing a structured and detailed framework for assessing Lean 4.0 readiness in the chemical industry.

In addition, data collection was conducted through a Delphi method-based questionnaire distributed to experts with in-depth knowledge of Lean 4.0 deployment, integrating lean principles and Industry 4.0 technologies. The expert panel consisted of three professionals from the basic chemical manufacturing industry, each closely involved in their company's Digital Transformation team. The data collection process followed a two-round Delphi method to refine and validate the assessment indicators. In the first round, experts reviewed the proposed indicators and eliminated 30 items deemed not directly relevant to the chemical industry or Industry 4.0, such as safety, machine learning, and inventory management. This refinement resulted in a framework with five dimensions and 127 indicators. In the second round, the Delphi method focused on determining the importance level of each remaining indicator using a five-point Likert scale, as described in Table 2. Each expert independently completed the questionnaire, ranking indicators from "completely unimportant" to "very important." The responses were then converted into triangular fuzzy numbers to handle variability in expert judgments.

The experts confirmed that the five dimensions—management, people, product, technology, and operation—remained relevant to Lean 4.0 in the chemical industry, while indicators with low or no relevance, such as safety, inventory management, waiting time, and overproduction, were removed. The collected responses were processed using triangular fuzzy numbers, where Likert scale values were converted into fuzzy numbers, followed by defuzzification to obtain precise, crisp values (non-fuzzy). According to [46], indicators with a crisp value of 70% or higher were considered valid, while 41 indicators failed to meet this threshold and were excluded. As a result, the final Lean 4.0 readiness assessment framework comprises five dimensions and 86 indicators, as detailed in Table 4.

Following the development of the Lean 4.0 Readiness Assessment Tool, as outlined in Table 4, companies perform self-assessments to evaluate their readiness level for each indicator. The self-assessment process determines the

Table 4. Dimensions and Indicators of Lean 4.0 Assessment tools for Chemical Industry

Management and Organization	
A1	Management support for Industry 4.0 transformation
A2	Commitment to active involvement of management
A3	Leadership attitude in the application of Lean
A4	Leadership attitude in the application of Industry 4.0 technology
A5	Lean approach strategy
A6	Industry 4.0 technology adoption strategy
A7	Management direction related to Continuous Improvement
A8	Management delegates work-related decisions to the workforce.
A9	Team works well organized

DOI:10.25077/josi.v23.n2.p283-298.2024

Table 4. (Cont.)

A10	Long-term plan for technological investment
A11	Allocation of human resources for technology investment
A12	There is a cost allocation for technology investment
A13	There is a genuine dedication to the elimination or reduction of all non-value-adding activities.
A14	There is a formal policy to encourage Industry 4.0 technology innovation
A15	There is a special team for Industry 4.0 transformation
A16	Implementation of improvement plan
A17	Production is 'pulled' in response to downstream consumer demand.
A18	Improvement / Kaizen
People and Culture	
B1	Lean Implementation
B2	Efficiency impact of Lean implementation
B3	Workflow balance
B4	Integration of Lean with Industry 4.0 principles
B5	Multi-functional employees
B6	Employee discipline towards time
B7	Employee commitment and work ethic
B8	There is a commitment to reduce production run lengths
B9	Employee Work attitude
B10	Employees are open to the application of new technology
B11	The workforce is empowered to implement changes and is engaged in development initiatives.
B12	The workforce consistently submits suggestions for individual and team-based development.
B13	Suppliers possess adaptable processes that can effortlessly accommodate fluctuations in demand.
B14	Competency Development
B15	There is an analysis of competency development needs related to Lean
B16	There is a competency development needs analysis related to Industry 4.0
B17	Lean related training
B18	Industry 4.0 technology training/workshop/certification available
B19	Employees have the opportunity to upgrade their skills according to industry trends
B20	The workforce is highly competent and trained in multiple areas, and a job rotation system is used.
B21	Effective quality processes and procedures have been established
Product and Service	
C1	Product customization rate
C2	Production rates fluctuate in accordance with the rates at which customers demand products.
C3	Customer feedback mechanism
C4	Data analysis to improve customer service
C5	Product integration with technology
C6	Added value to customers
Technology	
D1	Implementation of cyber security
D2	M2M connectivity (communication between machines) via internet/intranet
D3	Connectivity of systems in the company between different technical disciplines
D4	ERP implementation
D5	Implementation of machine learning
D6	RFID implementation
D7	Implementation of CAM (Computer Aided Manufacturing)

Table 4. (Cont.)

D8	Implementation of SCADA (Supervisory Control and Data Acquisition)
D9	Implementation of PLC (Programmable Logic Controller)
D10	Manual to digital process conversion
D11	Electronic data exchange (EDI)
Plant Operation	
E1	Digital storage of operation data
E2	Accuracy of data filling (Data accusation)
E3	Application of FIFO (First In First Out)
E4	Delivery time
E5	Standardization of supply chain flow
E6	Application of GPS monitoring system in products and components in the logistics system
E7	Implementation of real-time inventory control in products and components in the logistics system
E8	Use of IoT or sensors to manage the supply chain
E9	Logistics integration between the company and vendors/suppliers
E10	Deliveries are scheduled according to manufacturing requirements, ensuring they are not excessive and are delivered punctually.
E11	Production is mixed at the same process and facility
E12	Inventory buffers for supplies are strategically planned and established at the minimal acceptable thresholds.
E13	Suppliers are provided with a consistent and foreseeable timetable that does not involve any unforeseen alterations.
E14	Production is aligned with the customer's demand rate or takt time
E15	Stable supply in terms of quality, quantity, and schedule
E16	Material planning
E17	Company's automation process level
E18	Machine condition
E19	Worker scheduling
E20	Repetition of the same problem
E21	Application of PDCA (Plan Do Check Act)
E22	Application of RCA (Root Cause Analysis)
E23	Achievement of target and target indicators
E24	Real-time machine condition monitoring and OEE monitoring system
E25	Predictive maintenance
E26	Preventive maintenance
E27	Corrective maintenance
E28	Implementation of TPM (Total Productive Maintenance)
E29	Quality systems and processes are established to proactively mitigate the occurrence of problems.
E30	Scheduling of machines

extent to which each criterion is met, expressed as a percentage, thereby indicating the level of implementation. This self-evaluation is conducted across all 86 indicators, after which the results are aggregated to determine the average score for each dimension. The final readiness percentage is derived by computing the average of the dimension scores, based on responses provided by the company [33].

To visually represent the Lean 4.0 readiness levels, radar plots are employed. These plots display the five assessment dimensions, clearly highlighting strengths and weaknesses in each area. This visualization enables companies to identify low-scoring dimensions that require improvement while maintaining progress in areas where they already

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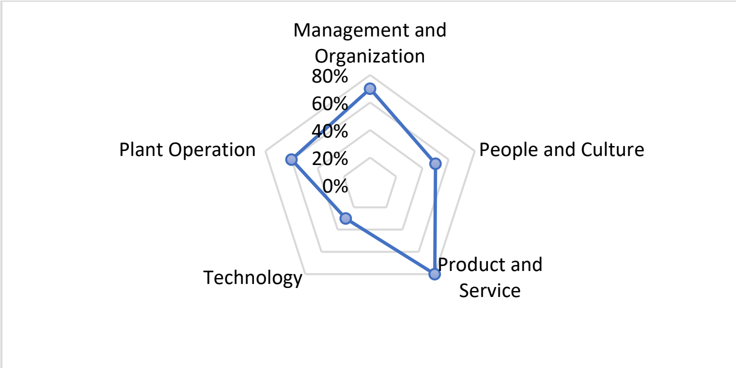

Figure 3. Radar plot for visualization of each dimension

excel. Figure 3 illustrates a typical radar plot for a company's Lean 4.0 readiness score, revealing that the lowest-scoring dimension is technology, with a readiness score of 15%. Since technology represents the weakest area, it should be prioritized, prompting companies to explore and adopt suitable technologies that can streamline business processes. Conversely, the highest-scoring dimension, "Product and Services," achieved a readiness score of 96%, indicating that this area is well-developed and requires minimal immediate intervention. By leveraging radar plot visualizations, companies can develop targeted improvement strategies to enhance their Lean 4.0 readiness and ensure a structured and effective transition toward Industry 4.0.

CONCLUSION

The Lean 4.0 Readiness Assessment Tool offers a comprehensive and systematic framework for evaluating both leanness level and Industry 4.0 readiness within the chemical industry, seamlessly integrating lean principles with digital transformation strategies. The model is structured around five core dimensions—management and organization, people and culture, products and services, technology, and plant operations—comprising 86 rigorously validated indicators that holistically assess the interplay between lean methodologies and Industry 4.0 adoption. The assessment results are visualized through radar charts, providing organizations with an intuitive representation of their capabilities, strengths, and areas requiring intervention, thereby enabling data-driven strategic decision-making. Beyond its analytical robustness, this tool holds substantial practical implications, empowering companies to precisely gauge their readiness for digital transformation, refine operational efficiencies, and formulate targeted interventions for Lean 4.0 implementation, ultimately fostering greater competitiveness, profitability, and long-term sustainability. However, despite its methodological rigor, this study is constrained by limited validation scope, as the tool has been tested within a single corporate setting, necessitating further empirical validation across a diverse range of chemical industry stakeholders to ensure its scalability, adaptability, and broader industrial applicability. Future research should focus on refining the model by incorporating weighted indicator evaluations to enhance precision and fairness in readiness measurement, while extending its application across multiple industry sectors would further bolster its generalizability, making it a robust and indispensable strategic instrument for Lean 4.0 adoption in the evolving landscape of industrial digital transformation.

ACKNOWLEDGMENTS

The authors sincerely thank the editors and reviewers for their invaluable contributions to this article. Their insightful feedback, constructive comments, and meticulous review have significantly enhanced the quality and clarity of this work. We deeply appreciate their dedication to academic excellence and their generous investment of time and effort

CONFLICT OF INTEREST

The authors declare no conflict of interest regarding the publication of this paper.

FUNDING

This research was funded by a Basic Research of Doctoral grant from the Directorate General High Education, Research and Technology Indonesia Contract Grant No: 038/E5/PG.02.00.PL/2024.

References

[1] D. M. Gligor and M. C. Holcomb, "Understanding the role of logistics capabilities in achieving supply chain agility: a systematic literature review," *Supply Chain Manag. An Int. J.*, vol. 17, no. 4, pp. 438–453, Jan. 2012, doi: 10.1108/13598541211246594.

[2] A. Schumacher, S. Erol, and W. Sihn, "A Maturity Model for Assessing Industry 4.0 Readiness and Maturity of Manufacturing Enterprises," *Procedia CIRP*, vol. 52, pp. 161–166, 2016, doi: 10.1016/j.procir.2016.07.040.

[3] D. R. Brousell, J. R. Moad, and P. Tate, "The next industrial revolution: how the internet of things and embedded, connected, intelligent devices will transform manufacturing," *Frost Sullivan, A Manuf. Leadersh. White Pap.*, 2014.

[4] G. Anand and P. T. Ward, "Fit, Flexibility and Performance in Manufacturing: Coping with Dynamic Environments," *Prod. Oper. Manag.*, vol. 13, no. 4, pp. 369–385, Dec. 2004, doi: 10.1111/j.1937-5956.2004.tb00224.x.

[5] A. Genovese, S. C. L. Koh, N. Kumar, and P. K. Tripathi, "Exploring the challenges in implementing supplier environmental performance measurement models: a case study," *Prod. Plan. Control*, vol. 25, no. 13–14, pp. 1198–1211, Oct. 2014, doi: 10.1080/09537287.2013.808839.

[6] P. Leitão, A. W. Colombo, and S. Karnouskos, "Industrial automation based on cyber-physical systems technologies: Prototype implementations and challenges," *Comput. Ind.*, vol. 81, pp. 11–25, 2016, doi: 10.1016/j.compind.2015.08.004.

[7] A. Rashid and B. Tjahjono, "The Management of Operations Achieving manufacturing excellence through the integration of enterprise systems and simulation," *Prod. Plan. Control*, vol. 7287, no. February, 2016, doi: 10.1080/09537287.2016.1143132.

[8] Y. Lu and X. Xu, "Resource virtualization: A core technology for developing cyber-physical production systems," *J. Manuf. Syst.*, vol. 47, pp. 128–140, 2018.

[9] A. D. Chandler, *Shaping the Industrial Century*, Harvard University Press, 2005, doi: 10.2307/j.ctv1pncqx2.

[10] M. Mahfud and Z. Sabara, *Industri Kimia Indonesia.* Yogyakarta, Indonesia: Deepublish, 2018.

[11] R. Y. Naulina et al., *Kimia Industri.* Bandung, Indonesia: CV Widina Media Utama, 2023..

[12] S. Chavush and R. Bikker, *A Manufacturing Company's Approach to the 2030 UN SDGs Affected by Institutional Differences and Theory,* Master's thesis, Jönköping Int. Business School, Jönköping Univ., Sweden, May 2023.

[13] PricewaterhouseCoopers, *Delivering the Sustainable Development Goals,* 2017. [Online]. Available: PwC Report.

[14] **BAPPENAS,** *Laporan Pelaksanaan Pencapaian TPB/SDGs Tahun 2021,* 2021. [Online]. Available: SDGs BAPPENAS.

[15] G. Beier, S. Niehoff, and M. Hoffmann, "Industry 4.0: A step towards achieving the SDGs? A critical literature review," *Discov. Sustain.*, 2021, doi: 10.1007/s43621-021-00030-1.

[16] Kementerian Perindustrian RI, *Making Indonesia 4.0: Peta Jalan Industri 4.0,* 2018. [Online]. Available: https://bsn.go.id/uploads/download/making_indonesia_4.0_-_kementerian_perindustrian.pdf.

[17] Germany Trade & Invest, *Industrie 4.0: Smart Manufacturing for the Future.* Germany: GTAI, 2014. [Online]. Available: https://www.pac.gr/bcm/uploads/industrie4-0-smart-manufacturing-for-the-future-en.pdf.

[18] M. Rüßmann, M. Lorenz, P. Gerbert, M. Waldner, J. Justus, and M. Harnisch, "Industry 4.0: The Future of Productivity and Growth in Manufacturing Industries," 2015.

[19] M. Sony and S. Naik, "Key ingredients for evaluating Industry 4.0 readiness for organizations: A literature review," *Benchmarking An Int. J.*, 2019, doi: 10.1108/BIJ-09-2018-0284.

[20] S. Mittal, M. A. Khan, D. Romero, and T. Wuest, "Smart manufacturing: Characteristics, technologies, and enabling factors," in *Engineering Manufacture*, 2017, doi: 10.1177/0954405417736547.

[21] S. Albukhitan, "Developing Digital Transformation Strategy for Manufacturing," *Procedia Comput. Sci.*, vol. 170, pp. 664–671, 2020, doi: 10.1016/j.procs.2020.03.173.

[22] S. Nambisan, "Digital Entrepreneurship: Toward a Digital Technology Perspective of Entrepreneurship," *Entrep. Theory Pract.*, vol. 41, no. 6, pp. 1029–1055, Nov. 2017, doi: 10.1111/etap.12254.

[23] G. Citybabu and S. Yamini, "Lean Six Sigma 4.0 – a framework and review for Lean Six Sigma practices in the digital era," 2023, doi: 10.1108/BIJ-09-2022-0586.

[24] A. Muhardono, C. Chalimah, and M. Diazwara, "Peran kemampuan pengguna teknologi informasi menuju transformasi sumberdaya manusia di era Revolusi Industri 4.0," *FIRM J. Manag. Stud.*, vol. 7, no. 1, pp. 81–92, 2022. [Online]. Available: FIRM Journal.

[25] H. Robinson, "Why do most transformations fail? A conversation with Harry Robinson," *McKinsey & Company*, 2019. [Online]. Available: McKinsey Report.

[26] T. ldanha, *Why Digital Transformations Fail: The Surprising Disciplines of How to Take Off and Stay Ahead.* Berrett-Koehler Publishers, 2019.

[27] T.ln, "What Lean Thinking has to Offer the Process Industries," *Chem. Eng. Res. Des.*, vol. 83, no. A6, pp. 662–673, 2005, doi: 10.1205/cherd.04351.

[28] F. W.z, P. D. Karningsih, and H. Supriyanto, "Penerapan Lean Manufacturing Untuk Mereduksi Waste di PT ARISU," *J. Tek. ITS*, vol. 1, no. 1, pp. F135–F140, 2012, doi: 10.12962/j23373539.v1i1.1777.

[29] M. H. Lia C. T. Wang, "Using enterprise architecture to integrate lean manufacturing, digitalization, and sustainability: A lean enterprise case study in the chemical industry," *Sustain.*, vol. 13, no. 9, 2021, doi: 10.3390/su13094851.

[30] Shift Indona"Masa Depan Lean di Era Industri 4.0," Mar. 30, 2021. Available: https://shiftindonesia.com/masa-depan-lean-di-era-industry-4-0/ (accessed Mar. 30, 2024).

[31] G. Hoellthaler.raunreuther, and G. Reinhart, "Digital lean production – An approach to identify potentials for the migration to a digitalized production system in SMEs from a lean perspective," *Procedia CIRP*, vol. 67, pp. 522–527, 2018, doi: 10.1016/j.procir.2017.12.255.

[32] Rakhmanhuda an.. Karningsih, "Development of lean assessment indicator: A case study," in *MATEC Web Conf.*, vol. 204, 2018, Art. no. 01010, doi: 10.1051/matecconf/201820401010.

[33] M. F. Brito, A. L. RsP. Carneiro, and M. A. Gonçalves, "A continuous improvement assessment tool, considering lean, safety and ergonomics," *Int. J. Lean Six Sigma*, vol. 11, no. 5, pp. 879–902, Jan. 2020, doi: 10.1108/IJLSS-12-2017-0144.

[34] D. D. Harjanto and P. Daingsih, "Pengembangan Dimensi dan Indikator Lean Assessment Tools UMKM di Indonesia," *Prozima*, vol. 5, no. 1, pp. 21–29, 2021, doi: 10.21070/prozima.v5i1.1426.

[35] D. N. Muhammad and P. D. Kisih, "Development of Lean Assessment Tool for Healthcare Industry," in *Int. Conf. Bus. Eng. Manag. 2020*, 2020.

[36] C. Lyons, K. Vidamour, R. nand M. Sutherland, "Developing an understanding of lean thinking in process industries," *Prod. Plan. Control*, vol. 22, no. 6, pp. 553–566, 2011, doi: 10.1080/09537287.2011.633576.

[37] S. Lyu, C. K. H. Hon, A. P. C. C,. K. W. Wong, and Y. J. J. Dai, "Relationships among safety climate, safety behavior, and safety outcomes for ethnic minority construction workers," *Int. J. Environ. Res. Public Health*, vol. 15, no. 3, p. 484, 2018, doi: 10.3390/ijerph15030484.

[38] P. O. P. Rahmatindar, M. L. SinggihnP. D. Karningsih, "Development Of Lean 4.0 Readiness Assessment Tool," *Sepuluh Nopember Institute of Technology*, 2024.

[39] P. L. King and J. S. King, *Value StreMping for the Process Industries*. Taylor & Francis, 2015.

[40] VDMA IMPULS, *Industry 4.0 Readiness: Online Self-Check for Businesses.* IMPULS Foundation, VDMA, 2015. [Online]. Available: https://www.industrie40-readiness.de/?lang=en.

[41] Singapore Economic Development Board, *The Smart Industry Readiness Index,* 2017. [Online]. Available: SIRI-Whitepaper.

[42] Kementerian Perindustrian Republik Indonesia, "Indonesia Industry 4.0 Readiness Index," 2018.\

[43] PricewaterhouseCoopers, *Industry 4.0 - Digital Operations Self-Assessment,* 2019. [Online]. Available: PwC Self-Assessment.

[44] W. Kosasih, I. N. Pujawan, and P. D. Karningsih, "Integrated Lean-Green Practices and Supply Chain Sustainability for Manufacturing SMEs: A Systematic Literature Review and Research Agenda," *Sustainability*, vol. 15, no. 16, 2023, doi: 10.3390/su151612192.

[45] M. Pagliosa and G. Tortorella, "Lean Manufacturing Future Research Directions," *Journal of Manufacturing Technology Management*, 2018, doi: 10.1108/JMTM-12-2018-0446.

[46] A. Pandor et al., "Delphi Consensus Reached to Produce a Decision Tool for Selecting Approaches for Rapid Reviews (STARR)," *Journal of Clinical Epidemiology*, vol. 114, pp. 22–29, 2019, doi: 10.1016/j.jclinepi.2019.06.005.

[47] S. J. Raval, R. Kant, and R. Shankar, "Benchmarking the Lean Six Sigma Performance Measures: A Balanced Scorecard Approach," *Benchmarking: An International Journal*, vol. 26, no. 6, pp. 1921–1947, 2019, doi: 10.1108/BIJ-06-2018-0160.

[48] M. J. Saary, "Radar Plots: A Useful Way for Presenting Multivariate Health Care Data," *Journal of Clinical Epidemiology*, vol. 60, pp. 311–317, 2008, doi: 10.1016/j.jclinepi.2007.04.021.

[49] S. A. Boamah, H. K. S. Laschinger, C. Wong, and S. Clarke, "Effect of transformational leadership on job satisfaction and patient safety outcomes," *Nursing Outlook*, vol. 66, no. 2, pp. 180-189, 2018. doi: 10.1016/j.outlook.2017.10.004.

APPENDIX

A.1. INDI 4.0 Dimensions and indicators

No	Dimension	Indicators
1	Plant Operation	Data Storage and Dissemination
		Smart Supply Chain and Logistics
		Autonomous Processes
		Intelligent Maintenance Systems
2	Management and Organization	Strategy and Leadership
		Investment for Industry 4.0
		Innovation Policy

DOI:10.25077/josi.v23.n2.p283-298.2024

A.1. (Cont.)

No	Dimension	Indicators
3	People and Culture	Culture
		Willing to Change
		Competence Development
4	Product and Services	Product Customization
		Data-driven Services
		Smart Products
5	Technology	Cyber Security
		Connectivity
		Smart Machines
		Digitalization

A.2. Dimensions for each LAT

No	Dimension	Lyons [36]	Boamah et al. [49]	Brito et al. [33]	Muhammad and Kisih [35]	Harjanto and Daingsih [34]
1	Quality	√		√	√	√
2	Performance Indicator		√	√		
3	Time	√		√	√	√
4	Process	√		√	√	√
5	Human Resources	√	√		√	√
6	Delivery	√			√	√
7	Customer				√	√
8	Inventory	√		√	√	√
9	Product and Material Flow			√		
10	Product Value			√		√
11	Supplier	√	√			√
12	Technology Upgradation		√		√	√
13	Continuous Improvement	√	√	√		√
14	Vertical Information System			√	√	√
15	Management Commitment	√	√	√	√	√
16	Cost				√	√
17	Safety			√		
18	Standards and Visual Management	√		√		
19	Physical Ergonomics			√		
20	Discipline		√	√		
21	Work Organization	√	√	√		
22	Planning Control & Execution		√			

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DOI:10.25077/josi.v23.n2.p283-298.2024