Tuijin Jishu/Journal of Propulsion Technology
ISSN: 1001-4055
Vol. 45 No. 3 (2024)

Exploring Industry 4.0 Maturity Models for Manufacturing

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Abstract:- This study seeks to conduct a theoretical review of existing Industry 4.0 (I4.0) Maturity Models (MM) within the manufacturing sector, aiming to provide large enterprises with a comprehensive understanding of contemporary advanced practices. By performing an extensive analysis of several maturity models proposed by industry bodies, this research encompasses various scopes and stages to elucidate the current landscape. The objective is to identify and delineate common scopes within these maturity models that are relevant to large/multinational enterprises. Key areas of focus include organizational strategy, smart factory, smart operations, smart products, vertical integration (VI), horizontal integration (HI), employees, leadership, customers, culture, governance, technology, data-driven governance, IT infrastructure, and information systems. The outcome of this literature review offers a synthesized understanding of how these scopes are addressed across different enterprises, providing valuable insights to navigate the industry 4.0 transformation effectively.

Keywords*: Maturity Models, Industry 4.0, Manufacturing*.

1. Introduction

Manufacturing companies worldwide face significant challenges stemming from contemporary environmental, societal, economic, and technological shifts. The future landscape of manufacturing necessitates companies to possess capabilities facilitating the agile and responsive management of their entire value chain. This entails the establishment of virtual and physical structures that enable seamless cooperation and rapid adaptation across the entirety of the lifecycle—from innovation to production and distribution (Bretthauer, 2015). In the current state of production technology, the drive for enhanced efficiency in manufacturing processes predominates. However, advancements in manufacturing efficiency primarily focus on individual firms rather than spanning the entire supply chain. Progress is observed across various fronts, including organizational-economic aspects like Lean Management, technological advancements such as laser technology and additive manufacturing, material innovations like nano materials and carbon fibers, and IT advancements such as RFID and embedded systems. These developments have resulted in notable but isolated improvements in process efficiency and product quality.

However, to realize and sustain high efficiency gains in manufacturing in the competitive landscape will demand a lot from digital integration and intelligentization. Both horizontal and vertical operations should be implemented across all participants in the value chain and all automation layers. The concept of Industry 4.0 (I4.0), along with other modern paradigms such as IoT, Industrial Internet, and Cloud-based Manufacturing, envisions futuristic factories that are fully integrated, operate intelligently, and require minimal human involvement. This idea represents aspirations for advanced manufacturing operations. Industry 4.0 represents the most recent technological advancements utilizing the internet as a foundation, along with additional technologies such as embedded systems, to connect physical objects, people, smart machines, and manufacturing processes regardless of organizational barriers, creating a highly interconnected and flexible value chain!

Fettermann et al. (2018) argue that, it has become clear that numerous companies struggle to fully understand the impact of I4.0 on their specific sectors and strategic objectives (Ruan et al., 2017). The absence of

comprehension makes it difficult to assess their advancement in I4.0 and hinders their ability to identify areas for improvement and put practical plans into action. This lack of understanding makes it impossible to evaluate their current progress in relation to the I4.0 vision, which limits their capacity to pinpoint specific areas that require improvement and implement workable projects.

In light of the growing concerns and dissatisfaction around I4.0, manufacturing organizations are in dire need of innovative approaches and resources to assist them in bringing their business strategies into compliance with operational reality. Within the context of Germany's 2020 technical growth agenda, the idea of "Industry 4.0" was first introduced at the Hannover Fair in 2011 (Schuh et al., 2017). By fusing the Internet of Things with Cyber-Physical Systems (CPS), Industry 4.0 represents a significant breakthrough in the industrial sector and acts as a roadmap for the digital transformation of production (Schuh et al., 2017). By fusing the Internet of Things with Cyber-Physical Systems (CPS), Industry 4.0 represents a significant breakthrough in the industrial sector and acts as a roadmap for the digital transformation of production (Schuh et al., 2017). According to Schuh et al. (2017), this stage of transformation has the potential to significantly alter industrial production by promoting efficiency, transparency, flexibility, cost-cutting, and innovation that will result in the creation of new business paradigms and service models.

A thorough implementation strategy is necessary for businesses to successfully restructure and improve their processes in accordance with I4.0 criteria. Maturity Models (MMs), well-known for enhancing organizational capacity through the establishment of progressive phases and goals, are an invaluable instrument for maneuvering through the industry 4.0 environment (Shohmohammadi et al., 2018). Maturity models provide an organized way to assess existing organizational maturity levels and direct development toward enhanced capabilities throughout organizational change.

The best way to solve this problem is to compare Industry 4.0 Maturity Model (I4.0-MM) developed by industry bodies, which will provide businesses with a roadmap for progressively, consistently, and successfully expanding their responsibilities in the industry 4.0 environment. Therefore, the purpose of this paper is to review existing maturity model framework and draw inferences from their best practices.

2. Literature Review

The benefits of I4.0 are manifold. By creating an environment that is both agile and responsive, manufacturers can achieve higher productivity and efficiency, leading to increased revenue growth. The ability to produce high-quality products more quickly and cost-effectively not only meets customer expectations but also provides a competitive advantage in the marketplace. Ultimately, smart manufacturing represents a forward-thinking shift towards more intelligent, efficient, and profitable production systems.

The adoption of smart manufacturing by Multi-National Companies (MNCs) has progressed significantly, with varying stages of implementation across different aspects of their operations. MNCs are increasingly integrating smart manufacturing technologies into their planning, production, operations, and logistics processes. This integration includes advanced data analytics for better decision-making, IoT for real-time monitoring, AI for predictive maintenance, and automation for enhanced efficiency. Different companies are at various stages of this transformation, continually exploring and integrating new technologies to stay competitive and meet evolving market demands. The impact of I4.0 on MNCs underscores its potential to revolutionize the manufacturing landscape, driving innovation and efficiency across global operations.

The systematic literature review of I4.0 maturity models reveal significant insights into the current landscape and the practical implementation of these models across various sectors. Treviño-Elizondo et al. (2023) propose a maturity model that integrates lean principles with I4.0 technologies, highlighting the synergy between these approaches to enhance value creation in organization. Ünlü et al. (2023) provide a comparative analysis of 22 maturity and readiness models, noting the lack of a universally accepted model and the need for practical application feedback. Bulina and Solopova (2023) present a digital maturity model specifically for the construction industry, emphasizing the integration of digital environments with Building Information Modeling

(BIM). Chekalina (2024) outlines an organizational maturity model focused on improving sociotechnical work systems within the manufacturing sector.

Implementing Industry 4.0 (I4.0) maturity models present several challenges that organizations must navigate to effectively transition to advanced manufacturing and digital operations. Some of the key challenges include:

- **Lack of Standardization**: There is no universally accepted I4.0 maturity model, leading to inconsistencies and difficulties in comparing and implementing different models across industries and regions (Ünlü, 2023).
- **Complexity of Integration**: Integrating various I4.0 technologies, such as IoT, big data analytics, and cyber-physical systems, with existing processes and systems can be complex and resource-intensive (Chekalina, 2024).
- **High Initial Investment**: The cost of implementing I4.0 technologies and upgrading infrastructure can be prohibitive for many organizations, particularly small and medium-sized enterprises (SMEs).
- **Skills Gap**: There is often a significant skills gap in the workforce, requiring substantial investment in training and development to equip employees with the necessary skills to operate and maintain I4.0 technologies (Treviño-Elizondo, 2023).
- **Resistance to Change**: Organizational culture and resistance to change can hinder the adoption of new technologies and processes. Leadership and change management strategies are crucial to overcoming this resistance (Bulina & Solopova, 2023).
- **Data Management**: Effective data management, including data collection, storage, and analysis, is critical for I4.0. Ensuring data quality, security, and privacy is a significant challenge.
- **Lack of Practical Feedback**: Many existing maturity models lack practical feedback and real-world application information, making it difficult for organizations to assess their effectiveness and applicability (Ünlü, 2023).

3. I4.0 Maturity Models

The paper reviews three existing I4.0 maturity models, examining their scope, methodology, and fit.

A. The Connected Enterprise Maturity Model

The Rockwell Automation (2015) Connected Enterprise Maturity Model provides a framework for manufacturing organizations to integrate Operations Technology (OT) with Information Technology (IT), unlocking significant productivity and cost savings. This model outlines a five-phase approach to progressively enhance OT/IT networks, optimize data usage, and secure infrastructures, culminating in the creation of a fully integrated intelligent enterprise.

Key Components

- **Convergence of OT and IT**

The integration of OT and IT fosters collaboration across the enterprise, enhancing visibility and decision-making capabilities. This convergence is fundamental for creating a connected enterprise that can respond swiftly and effectively to both internal and external demands.

- **Real-time Decision-making**

Utilizing real-time data allows for proactive management of activities, ensuring that decisions are based on the most current and accurate information. This capability is crucial for maintaining competitive advantage and operational efficiency.

- **Data Security**

Securing the free flow of data is paramount. The model emphasizes the importance of mitigating cyberattack risks to protect data integrity from the enterprise level to individual endpoints.

- **Smart Networks**

Optimizing asset management, energy use, and equipment reliability is achieved through the implementation of smart networks. These networks enable more efficient operations and reduce downtime, contributing to overall productivity gains.

- **Productivity Gains**

Automation and real-time analytics reduce the need for human intervention, thereby increasing productivity and allowing for continuous improvements in processes.

- **Continuous Improvement**

Continuous improvement is facilitated by real-time analytics, which provide insights that can be used to make ongoing enhancements to processes and systems.

- **Knowledge Management**

The model addresses the challenge of knowledge retention, ensuring that critical information is preserved even as experienced employees retire. This is achieved through better information flow and documentation practices.

- **Integrating Modern and Legacy Systems**

One of the challenges highlighted by the model is the integration of modern systems with existing legacy infrastructure. This integration is essential for achieving a seamless connected enterprise.

- **Strategic Partnerships**

The model underscores the importance of strategic partnerships with technology leaders like Cisco, Microsoft, and Panduit. These collaborations are vital for embedding OT/IT seamlessly into the enterprise infrastructure.

The Connected Enterprise Maturity Model explains how the integration between OT and IT is transforming manufacturing by providing better visibility and enabling real-time decision-making. It highlights the importance of real-time data monitoring for effective internal and external operations and details the challenges and opportunities associated with this integration.

Five-Stage Maturity Model

1. **Assessment**: Evaluate current OT/IT infrastructure, controls, devices, networks, and security policies.
2. **Secure and Upgraded Networks**: Upgrade OT/IT infrastructure to ensure secure, flexible connectivity from the plant floor to the enterprise level.
3. **Organized Working Data Capital:** Standardize and contextualize data to improve business processes and derive actionable insights.
4. **Analytics**: Implement analytics to meet real-time information needs, define protocols, and authorize access, driving further improvements.
5. **Collaboration**: Foster predictive capabilities, efficient production planning, and improved supplier and customer relationships.

B. The Smart Industry Readiness Index

The Smart Industry Readiness Index (SIRI) has been developed by the Economic development Board of Singapore, in collaboration with TÜV SÜD, to catalyze the transformation of manufacturing industries. It provides a holistic framework and assessment tool that enables companies to understand their current level of

Industry 4.0 maturity, identify gaps, and craft a strategic roadmap for continuous improvement. The three basic building blocks are: Process Technology and Organization—eight pillars and 16 dimensions to help companies build future-ready capabilities.

SIRI describes the coming together of the physical and digital worlds to revolutionize big data-driven robotics and additive manufacturing. It is based on the premise of Singapore's manufacturing capabilities and the national aspiration to grow and transform further into advanced manufacturing.
The SIRI framework defines the three building blocks-the process, technology, and organization underlying them, and their interaction; eight pillars; and 16 dimensions to assess Industry. As part of the framework, an assessment matrix is developed that allows an organization to perform a self-assessment in regard to its existing state and the areas in which it needs to improve among the 16 dimensions.
The SIRI LEAD Framework describes a continuous, four-stage process that companies are to use in attacking this transformation of Industry 4.0—Learn, Evaluate, Architect, Deliver. The framework highlights the role of emerging new digital technologies such as cloud computing, IoT, and machine learning in creating hyper-connected industrial landscapes. It also emphasizes on strategic partnerships and collaboration among companies, industry experts, and government to drive the adoption of Industry 4.0.
At the core of the framework is the foundation that data is a strategic asset: Company's need to build infrastructure toward connectivity and intelligence.

Key Components

- **Maturity Assessment Matrix**: The self-diagnostic tool to appraise the current maturity levels of Industry 4.0.
- **Three Building Blocks**: Process Technology and Organization are key for transforming into future-ready plants.
- **Eight Pillars**: The most important of these elements are Operations, Supply Chain, Product Lifecycle, Automation, Connectivity, Intelligence, Talent Readiness, and Structure & Management.
- **LEAD Framework**: The four-step iterative improvement process; Learn, Evaluate, Architect, and Deliver.
- **Global Relevance**: This course is developed to assist companies anywhere in the world, regardless of their size and industry.
- **Collaboration**: Fosters partnership of companies with industry and government to ensure the right direction of successful transformation.
- **Data Utilization**: Data is to be taken care of as a strategic asset for growth and saving costs.
- **Digital Transformation**: Emphasizes the need for the different intelligent systems to be integrated and connected to ensure their efficient operation.
- **Technological Integration**: Technology is prioritized to aid automation connectivity and intelligence as drivers for the adoption of Industry 4.0.
- **Continuous Improvement**: SIRI frameworks and tools are a live blueprint for continual development in Industry 4.0 initiatives.

C. The IMPULS Framework

Lichtblau et al. (2015) and VDMA (Verband Deutscher Maschinen- und Anlagenbau) developed a comprehensive IMPULS Industry 4.0 readiness model, which is widely accepted and utilized to help organizations assess their current state and future steps towards Industry 4.0 implementation. The model evaluates readiness across six key dimensions:

- **Strategy and Organization**: Evaluates the strategic alignment and organizational culture towards Industry 4.0.
- **Smart Factory:** Assesses the level of automation and self-organization in production processes.
- **Smart Operations:** Focuses on the integration of IT systems and the use of data to optimize operations.
- **Smart Products:** Involves equipping physical products with ICT components for data collection and communication.
- **Data-Driven Services:** Looks at the use of data analytics to enhance service offerings and business models.
- **Employees:** Measures the skills and readiness of the workforce to adapt to digital changes.

The IMPULS model classifies readiness into six levels, ranging from Level 0 (Outsiders) to Level 5 (Top Performers). Each level has distinct criteria that organizations must meet to advance to the next stage.

- **Level 0 (Outsiders):** Organizations with minimal or no planning or implementation of Industry 4.0 initiatives.
- **Levels 1 to 5:** Represent a gradual progression through increasing degrees of digital integration, automation, and optimization, ultimately achieving complete implementation of Industry 4.0 capabilities.

The IMPULS framework is crucial for assessing manufacturing companies' readiness for Industry 4.0. It evaluates key dimensions like strategy, processes, technology, and organizational readiness through surveys, interviews, and data analysis. Implementing Industry 4.0 technologies can significantly enhance productivity and competitiveness by optimizing processes and leveraging advanced technologies such as IoT and machine learning. Continuous improvement, resource allocation, and collaboration within and outside the organization are emphasized. Globally applicable, the IMPULS tool identifies strengths and weaknesses to help manufacturers harness digital transformation benefits effectively.

4. Conclusion

The paper examines the current I4.0 maturity models that are proposed by industry bodies. By incorporating the proposed adaptations, these models can be made more relevant and useful for manufacturing companies, helping them to overcome the barriers to adopting advanced manufacturing technologies and to benefit from the opportunities offered by I4.0. This review provides valuable insights for manufacturing companies, highlighting the need for more tailored support and resources to help organizations navigate the complex transition towards I4.0. The adoption of I4.0 will pose high entry barriers to competition and reduce the risks associated with managing critical change, ultimately supporting the growth and competitiveness of the manufacturing sector.

References

[1] S. Chen, B. Mulgrew, and P. M. Grant, “A clustering technique for digital communications channel equalization using radial basis function networks,” IEEE Trans. on Neural Networks, vol. 4, pp. 570-578, July 1993.

[2] A. R. Bulina, N. A. Solopova, “Maturity model for assessing digitalization process of construction industry companies,”. E-Management, vol. 6(2), pp. 4-13, 2023. https://doi.org/10.26425/2658-3445-2023-6-2-4-13

[3] B. L. Treviño-Elizondo, and H. García-Reyes, “What does Industry 4.0 mean to Industrial Engineering Education?,” Procedia Computer Science, vol. 217, pp. 876–885. 4th International Conference on Industry 4.0 and Smart Manufacturing, 2023. https://doi.org/10.1016/j.procs.2022.12.284

[4] D. C. Fettermann, C. G. S. Cavalcante, T. D. D. Almeida, and G. L. Tortorella, “How Does Industry 4.0 Contribute to Operations Management?,” Journal of Industrial and Production Engineering, vol. 35 (4), pp. 255–268, 2018. doi:10.1080/21681015.2018.1462863

[5] G. Schuh, R. Anderl, J. Gausemeier, M. Hompel, W. Wahlster, "Industrie 4.0 maturity index. Managing the digital transformation of companies," Acatech – National Academy of Science and Engineering, 2017. https://www.acatech.de/wp-content/uploads/2018/03/acatech_STUDIE_Maturity_Index_eng_WEB.pdf

[6] H. Ünlü, O. Demirörs, and V. Garousi, (2023). "Readiness and maturity models for Industry 4.0: A systematic literature review," Journal of Software: Evolution and Process, vol. 35(4), e2641, 2023. https://doi.org/10.1002/smr.2641

[7] K. Lichtblau, V. Stich, R. Bertenrath, M. Blum, M. Bleider, A. Millack, K. Schmitt, E. Schmitz, and M. Schröter, (2015). "IMPULS-industrie 4.0-readiness," Impuls-Stiftung des VDMA, Aachen-Köln, 2015.

[8] Rockwell Automation. (2015). The Connected Enterprise Maturity Model. Retrieved from https://www.rockwellautomation.com/en-us/company/news/blogs/the-connected-enterprise-maturity-model--metrics-that-matter.html

[9] V. Chekalina, "Analysis of Human Performance in Manufacturing Framework of Industry 4.0," Journal of Enterprise and Business Intelligence, vol. 4(1), 2024. ISSN: 2789-5181.