



Analysis of Indonesian Industry Readiness for the Adoption of Autonomous Manufacturing Systems in the Era of Industry 4.0

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ABSTRACT

The rapid advancement of Industry 4.0 technologies has accelerated the transition from conventional manufacturing systems toward Autonomous Manufacturing Systems (AMS), which integrate Artificial Intelligence (AI), Industrial Internet of Things (IIoT), robotics, cyber-physical systems, digital twins, and big data analytics to enable intelligent, self-optimizing, and highly efficient production processes. Given the increasing importance of autonomous manufacturing for enhancing industrial competitiveness, this study aims to assess the readiness of Indonesian manufacturing industries to adopt Autonomous Manufacturing Systems. A mixed-methods approach was employed, combining quantitative and qualitative techniques. Data were collected through questionnaires, interviews, observations, and secondary sources involving respondents from the automotive, electronics, food and beverage, and textile sectors. The collected data were analyzed using descriptive statistics, readiness index calculations, gap analysis, Structural Equation Modeling (SEM), thematic analysis, and content analysis. The results indicate that the overall readiness level of Indonesian manufacturing industries is moderate. However, human resource readiness and cybersecurity readiness remain significant challenges due to shortages of specialized talent, limited AI-related competencies, insufficient workforce training, and varying levels of cybersecurity preparedness. The study also found substantial disparities between large enterprises and SMEs in terms of technology adoption and resource availability. The study concludes that while Indonesian manufacturing industries have established a foundation for autonomous manufacturing adoption, further improvements in workforce development, technology integration, cybersecurity infrastructure, and policy support are required. To accelerate the transition toward autonomous manufacturing, collaborative efforts among industry, government, and educational institutions are essential to strengthen technological capabilities, develop skilled human resources, and create a supportive innovation ecosystem.

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1. INTRODUCTION

The manufacturing sector has undergone significant transformation over the past few decades due to rapid technological advancements and increasing global competition. The emergence of Industry 4.0 has revolutionized traditional manufacturing systems by integrating digital technologies into industrial processes (Zhou et al., 2015). Industry 4.0 emphasizes the convergence of physical production systems with digital technologies, enabling intelligent decision-making, real-time monitoring, and interconnected production environments. More recently, the concept of Industry 5.0 has emerged, extending beyond automation and efficiency by emphasizing human-centric, resilient, and sustainable manufacturing systems. Together, these industrial paradigms are reshaping how manufacturing organizations operate and compete in the global market.

One of the most significant developments associated with Industry 4.0 and Industry 5.0 is the transition from conventional manufacturing systems toward autonomous manufacturing systems (Nahavandi, 2019). Traditional manufacturing relies heavily on human intervention for monitoring, controlling, and optimizing production activities. In contrast, autonomous manufacturing systems utilize advanced technologies that enable machines, equipment, and production processes to operate with minimal human involvement. These systems can independently collect data, analyze information, make decisions, and adjust production parameters in real time to achieve optimal performance.

The development of autonomous manufacturing systems is supported by several key technologies. Artificial Intelligence (AI) enables machines to perform intelligent decision-making, predictive maintenance, and process optimization (Andronie et al., 2021). The Industrial Internet of Things (IIoT) facilitates communication among machines, sensors, and production systems through interconnected networks. Machine Learning algorithms allow systems to learn from historical and real-time data to improve operational efficiency continuously. Advanced robotics enhances automation capabilities by performing complex tasks with high precision and consistency. Cyber-Physical Systems (CPS) integrate physical machinery with computational intelligence, enabling seamless interaction between digital and physical environments. Digital Twin technology creates virtual representations of physical systems for simulation, monitoring, and optimization purposes. Additionally, Big Data Analytics provides valuable insights from large volumes of industrial data, supporting informed decision-making and continuous improvement.

The adoption of autonomous manufacturing systems offers numerous benefits for industrial organizations. Autonomous systems can significantly improve productivity by reducing operational downtime and optimizing resource utilization (Singh, 2020). They can lower production costs through increased efficiency, predictive maintenance, and reduced waste generation. Product quality can be enhanced through real-time monitoring and automated quality control mechanisms. Furthermore, autonomous manufacturing enables flexible production processes that can rapidly adapt to changing customer demands and market conditions. These advantages contribute to increased global competitiveness, allowing industries to compete more effectively in increasingly dynamic and technology-driven markets.

In Indonesia, the manufacturing sector plays a crucial role in national economic development and remains one of the largest contributors to the country's Gross Domestic Product (GDP). Recognizing the strategic importance of industrial transformation, the Indonesian government introduced the Making Indonesia 4.0 roadmap as a national strategy to accelerate the adoption of advanced manufacturing technologies. This initiative prioritizes the integration of digital technologies across key industrial sectors, including food and beverage, automotive, electronics, chemicals, and textiles. In addition, various smart factory programs and digital transformation policies have been implemented to encourage industrial modernization and strengthen the competitiveness of domestic manufacturing industries.

Despite these initiatives, the level of digital transformation across Indonesian industries remains uneven. Large-scale enterprises generally possess greater financial resources, technological infrastructure, and skilled personnel to implement advanced manufacturing technologies (Manyika et al., 2012). Conversely, many small and medium-sized enterprises (SMEs) continue to face challenges related to limited investment capacity, insufficient technological expertise, inadequate digital infrastructure, and workforce skill gaps. As a result, the readiness of

Indonesian industries to transition from basic digitalization toward fully autonomous manufacturing systems remains uncertain.

Several important questions therefore arise regarding the current state of industrial readiness in Indonesia. First, are Indonesian manufacturing industries adequately prepared to adopt autonomous manufacturing systems? Second, what technological, organizational, and human resource factors influence the readiness of industries to implement autonomous manufacturing technologies? Third, what barriers and challenges hinder the successful adoption of autonomous manufacturing systems within the Indonesian industrial context? Addressing these questions is essential for understanding the current position of Indonesian manufacturing and identifying strategies to support future industrial transformation.

Research on Industry 4.0, smart manufacturing, and autonomous manufacturing readiness has grown significantly over the last decade as industries worldwide seek to leverage digital technologies to improve operational efficiency and competitiveness (Rüßmann et al., 2015). Existing studies have primarily focused on Industry 4.0 readiness assessment, technology adoption factors, implementation barriers, and digital transformation strategies. However, research specifically examining the readiness of industries for fully autonomous manufacturing systems remains relatively limited, particularly within the Indonesian context.

One of the earliest studies examining industrial readiness in Indonesia was conducted by Simamora, Asmara, Achelia, and Maulana (2020). Their study, entitled *Towards Industry 4.0: Is Indonesia's Manufacturing Industry Ready to Transform?*, evaluated the preparedness of Indonesian manufacturing firms for digital transformation. The authors highlighted that although the manufacturing sector plays a strategic role in Indonesia's economy, many firms still face challenges related to research and development investment, technological capability, and human resource competence. The study concluded that substantial efforts are required to enhance the readiness of Indonesian industries for advanced manufacturing technologies.

In the same year, Almamalik (2020) developed a maturity model specifically designed to assess the readiness of Indonesian manufacturing companies for Industry 4.0 implementation. The proposed model consisted of five major dimensions and thirty-four sub-dimensions that evaluate technological, organizational, and operational readiness. The study emphasized the importance of structured assessment frameworks to guide manufacturing companies in their digital transformation journey and to identify areas requiring improvement before implementing advanced manufacturing technologies.

At the international level, Hizam-Hanafiah, Soomro, and Abdullah (2020) conducted a comprehensive systematic literature review of Industry 4.0 readiness models. By analyzing ninety-seven academic and industry publications, the authors identified critical dimensions commonly used to measure readiness, including technology, strategy, organizational structure, culture, leadership, workforce capability, and operational processes. Their findings provided an important theoretical foundation for subsequent readiness assessment studies and highlighted the need for more context-specific readiness frameworks.

As Industry 4.0 technologies became increasingly adopted, researchers began investigating implementation challenges. Derigent, Cardin, and Trentesaux (2020) examined the role of intelligent manufacturing control architectures in supporting Industry 4.0 environments. Their study demonstrated that autonomous and interconnected manufacturing entities are essential for achieving flexible and adaptive production systems. The authors further argued that future manufacturing systems would increasingly rely on decentralized decision-making and autonomous operational capabilities, concepts that directly support the development of autonomous manufacturing systems.

Previous studies have extensively examined the adoption of Industry 4.0 technologies, digital transformation, and smart manufacturing practices in various industrial sectors (Ghobakhloo, 2020). However, most existing research focuses on general digitalization efforts, technology acceptance, or Industry 4.0 implementation maturity. Limited attention has been given to evaluating industrial readiness specifically for autonomous manufacturing systems, which represent a more advanced stage of industrial transformation characterized by intelligent, self-optimizing, and self-adaptive production processes. Consequently, there remains a significant research gap concerning the

preparedness of Indonesian industries to embrace autonomous manufacturing technologies and the factors influencing successful implementation.

Based on these considerations, this study aims to assess the readiness level of Indonesian industries for the adoption of autonomous manufacturing systems (Rezqianita & Ardi, 2020). Specifically, the research seeks to identify technological, organizational, and human resource factors that influence readiness while also examining the barriers and opportunities associated with implementation. Through a comprehensive assessment, the study intends to provide a clearer understanding of the current state of industrial preparedness and identify areas requiring further development.

The findings of this research are expected to contribute to multiple stakeholders. For industry practitioners, the study provides insights into critical readiness factors and strategic considerations for autonomous manufacturing adoption. For policymakers, the results can support the formulation of policies and programs that facilitate industrial digital transformation and technological innovation. For researchers, the study contributes to the growing body of knowledge on advanced manufacturing systems and industrial readiness assessment. Furthermore, technology providers can utilize the findings to develop solutions that better address the needs and challenges of Indonesian industries. Ultimately, this research contributes to supporting Indonesia's transition toward a more intelligent, competitive, and sustainable manufacturing ecosystem in the era of Industry 4.0 and Industry 5.0

2. RESEARCH METHOD

This study employs a mixed-methods research approach to comprehensively assess the readiness of Indonesian manufacturing industries for the adoption of Autonomous Manufacturing Systems (AMS). The mixed-methods approach combines quantitative and qualitative techniques to provide a more holistic understanding of industrial readiness. Quantitative methods are used to measure the level of readiness across different dimensions and identify significant relationships among readiness factors, while qualitative methods are employed to explore challenges, opportunities, and contextual factors that influence the implementation of autonomous manufacturing technologies. The integration of both approaches allows for a deeper analysis of technological, organizational, human resource, cybersecurity, and regulatory aspects affecting industrial transformation.

The research is designed using a readiness assessment framework that integrates concepts from the Technology Readiness Index (TRI), Industry 4.0 Maturity Models, and Smart Manufacturing Readiness Assessment frameworks (Lin et al., 2020). These models provide a systematic basis for evaluating an organization's preparedness to adopt advanced manufacturing technologies. The framework developed in this study evaluates readiness through multiple dimensions that collectively determine the capability of manufacturing firms to transition from conventional production systems toward intelligent and autonomous manufacturing environments. The assessment model is intended to identify current readiness levels, existing gaps, and strategic areas requiring improvement before large-scale implementation of autonomous manufacturing systems.

The target population of this study consists of manufacturing companies operating in Indonesia (Nawanir et al., 2013). To ensure representation across different industrial sectors, the study focuses on several key manufacturing industries that are strategically important to the national economy, including the automotive, electronics, food and beverage, and textile sectors. These sectors have been prioritized because they are among the industries targeted by national digital transformation initiatives and have varying levels of technological adoption. The sample is selected using purposive sampling techniques, where respondents are chosen based on their knowledge and involvement in industrial operations and digital transformation activities. The respondents include factory managers, production engineers, digital transformation officers, operations managers, information technology specialists, and industry experts who possess relevant experience regarding manufacturing processes and technological implementation.

Data collection is conducted through multiple sources to enhance the validity and reliability of the findings (Zohrabi, 2013). Primary data are obtained through structured questionnaires distributed to selected respondents across manufacturing companies. The questionnaire is designed to measure perceptions and evaluations regarding various readiness dimensions using a five-point Likert scale ranging from strongly disagree to strongly agree. In addition to the questionnaire survey,

semi-structured interviews are conducted with industry experts, senior managers, and digital transformation leaders to obtain in-depth insights into organizational experiences, implementation challenges, and future expectations concerning autonomous manufacturing systems. Observational data may also be collected through site visits to selected manufacturing facilities to examine existing automation practices and technological infrastructure. Secondary data are gathered from company reports, government publications, industry association reports, policy documents, and relevant academic literature to support the analysis and provide contextual understanding of industrial digitalization in Indonesia.

The readiness assessment framework used in this study consists of five major dimensions (Pirola et al., 2020). The first dimension is technological readiness, which evaluates the availability and capability of technological infrastructure necessary for autonomous manufacturing. This dimension includes automation infrastructure, deployment of industrial sensors, integration of Industrial Internet of Things (IIoT) technologies, data analytics capabilities, artificial intelligence implementation, machine connectivity, and digital monitoring systems. High technological readiness indicates that an organization possesses the technological foundation required to support autonomous production processes.

The second dimension is organizational readiness, which assesses the internal capacity of organizations to support technological transformation. This dimension examines the existence of digital transformation strategies, leadership commitment, investment capability, organizational flexibility, change management practices, and innovation culture. Organizational readiness is considered critical because successful implementation of autonomous manufacturing requires strategic vision, management support, and continuous organizational adaptation.

The third dimension is human resource readiness, which focuses on workforce preparedness for operating and managing advanced manufacturing technologies (Vrchota et al., 2019). Indicators within this dimension include employee digital skills, artificial intelligence literacy, technical competency, training and development programs, workforce adaptability, and the availability of specialized talent. Since autonomous manufacturing systems rely heavily on advanced technologies, the readiness of human resources plays a significant role in determining implementation success.

The fourth dimension is cybersecurity readiness, which evaluates an organization's capability to protect digital manufacturing environments from cyber threats and operational disruptions (Georgiadou et al., 2022). This dimension includes data protection mechanisms, network security systems, cybersecurity awareness, risk management practices, incident response capabilities, and compliance with information security standards. As manufacturing systems become increasingly interconnected, cybersecurity readiness becomes essential for maintaining operational reliability and protecting sensitive industrial data.

The fifth dimension is regulatory readiness, which examines the external environment supporting autonomous manufacturing adoption. This dimension includes government support programs, industrial regulations, standards compliance, digital transformation policies, technology incentives, and the overall policy environment. Regulatory readiness is important because government policies and institutional support can significantly influence the speed and effectiveness of industrial transformation efforts.

The collected quantitative data are analyzed using descriptive statistical techniques to determine the overall readiness level of Indonesian manufacturing industries (Prakosa et al., 2024). Statistical measures such as mean scores, standard deviations, percentages, and readiness indices are calculated for each readiness dimension. A readiness index is developed to classify organizations into different readiness categories, ranging from very low readiness to very high readiness. Gap analysis is also performed to identify discrepancies between current readiness levels and desired conditions for autonomous manufacturing implementation. Furthermore, Structural Equation Modeling (SEM) is employed to examine the relationships among technological, organizational, human resource, cybersecurity, and regulatory factors and their influence on overall readiness.

Qualitative data obtained from interviews and observations are analyzed using thematic analysis and content analysis techniques (Prakosa et al., 2024). Thematic analysis is used to identify recurring patterns, themes, and insights related to implementation challenges, strategic

opportunities, organizational experiences, and future expectations. Content analysis is conducted to systematically interpret textual information from interviews, reports, and policy documents. The qualitative findings complement the quantitative results by providing deeper explanations of readiness conditions and contextual factors affecting autonomous manufacturing adoption.

To ensure the reliability and validity of the research instruments, a pilot test is conducted before full-scale data collection. Reliability is assessed using Cronbach's Alpha coefficients to evaluate internal consistency among questionnaire items. Construct validity is examined through expert review and factor analysis procedures. Triangulation of multiple data sources, including questionnaires, interviews, observations, and secondary documents, is also employed to enhance the credibility and robustness of the research findings.

Through the integration of quantitative and qualitative methodologies, this study provides a comprehensive assessment of the readiness of Indonesian manufacturing industries to adopt autonomous manufacturing systems. The research methodology enables the identification of critical readiness factors, existing barriers, and strategic opportunities that can support Indonesia's transition toward intelligent, data-driven, and autonomous industrial operations.

3. RESULT AND DISCUSSIONS

3.1 Profile of Respondents

The respondents were drawn from several major manufacturing industries that play significant roles in Indonesia's industrial development. These sectors included the automotive, electronics, food and beverage, and textile industries. The automotive sector represented companies engaged in vehicle assembly, component manufacturing, and industrial automation activities. The electronics sector consisted of firms involved in the production of consumer electronics, electrical equipment, and digital devices. Respondents from the food and beverage industry represented manufacturers that have increasingly adopted automation technologies to improve production efficiency and product quality. Meanwhile, the textile sector included companies involved in textile processing, garment manufacturing, and related production activities. The inclusion of these sectors provided a comprehensive perspective on the readiness of industries with varying levels of technological sophistication and digital transformation maturity.

The participating companies varied considerably in size, allowing the study to capture readiness conditions across different organizational scales (Holt et al., 2007). Large enterprises constituted a significant proportion of the sample due to their greater involvement in digital transformation initiatives and advanced manufacturing technologies. These organizations typically possessed larger workforces, higher annual revenues, and more substantial investments in automation and digital infrastructure. Medium-sized enterprises were also well represented, reflecting their growing interest in adopting Industry 4.0 technologies to enhance competitiveness. In addition, several small manufacturing enterprises participated in the study, providing valuable insights into the challenges and opportunities faced by smaller organizations during digital transformation. The diversity in company size enabled the study to compare readiness levels between organizations with different resource capacities and operational capabilities.

Geographically, the respondents represented manufacturing companies located across several major industrial regions in Indonesia (Sjöberg & Sjöholm, 2004). A large proportion of respondents were based in Java, particularly in the provinces of West Java, Central Java, East Java, and the Special Capital Region of Jakarta, which collectively serve as the country's primary manufacturing hubs. Additional respondents were drawn from industrial centers in Sumatra, Kalimantan, Sulawesi, and Bali, ensuring broader regional representation. The geographic diversity of the sample allowed the study to examine potential differences in readiness levels associated with regional variations in infrastructure availability, technological development, and access to government support programs. It also provided a more comprehensive understanding of the state of autonomous manufacturing readiness throughout Indonesia rather than focusing solely on highly industrialized regions.

The participating companies also varied in terms of their years of operation. Some organizations had been operating for more than thirty years and possessed extensive experience in manufacturing activities, established operational procedures, and mature organizational structures.

Other companies had operated for between ten and thirty years and were actively modernizing their production systems through digital transformation initiatives. A smaller number of respondents represented relatively young manufacturing firms that had been established within the last decade. These newer companies often demonstrated greater flexibility in adopting emerging technologies due to fewer legacy systems and more agile organizational structures. The inclusion of companies with different operational histories enabled the study to investigate whether organizational age influences readiness for autonomous manufacturing adoption.

3.2 Readiness Assessment Results

The readiness assessment was conducted to evaluate the preparedness of Indonesian manufacturing industries for the adoption of Autonomous Manufacturing Systems (AMS). The assessment focused on five major dimensions, namely technological readiness, organizational readiness, human resource readiness, cybersecurity readiness, and regulatory readiness. The findings indicate that the overall readiness level of Indonesian manufacturing industries can be categorized as moderate, suggesting that while significant progress has been made in digital transformation and industrial automation, several critical challenges remain before fully autonomous manufacturing systems can be implemented on a large scale.

Technological readiness represents one of the most important dimensions influencing the successful adoption of autonomous manufacturing systems (Abd Jamil et al., 2024). The findings reveal considerable variation in technological capability among manufacturing companies, particularly between large enterprises and small and medium-sized enterprises (SMEs).

In terms of automation adoption, large manufacturing firms demonstrated relatively high levels of automation across production processes. Many companies have implemented automated production lines, robotic assembly systems, automated material handling equipment, and computer-controlled machinery. These technologies have enabled organizations to improve operational efficiency, reduce production errors, and enhance product consistency. However, SMEs continue to rely heavily on semi-automated or manual production systems due to financial limitations and restricted access to advanced technologies.

The level of Artificial Intelligence (AI) utilization also varied significantly among respondents (Abdullah & Fakieh, 2020). Large enterprises increasingly employ AI-based solutions for predictive maintenance, quality inspection, production scheduling, demand forecasting, and process optimization. AI applications allow organizations to analyze large volumes of operational data and make intelligent decisions in real time. In contrast, most SMEs reported limited AI adoption due to inadequate technical expertise, insufficient investment resources, and uncertainty regarding implementation benefits.

The implementation of the Industrial Internet of Things (IIoT) has expanded across many manufacturing facilities. Respondents reported increasing deployment of connected sensors, machine-to-machine communication systems, and real-time monitoring platforms. IIoT technologies enable the collection and transmission of operational data throughout the production process, supporting better visibility and performance management. Nevertheless, the degree of integration remains uneven, with many organizations still operating isolated systems that lack full interoperability.

The adoption of smart factory technologies, including digital twins, advanced analytics platforms, cloud-based manufacturing systems, and cyber-physical systems, remains at an early stage for most organizations (Tao et al., 2019). Although several large corporations have initiated smart factory projects, widespread implementation is still limited. Overall, the findings indicate that technological readiness is relatively high among large industries but remains moderate to low among SMEs. This disparity highlights the need for greater support to accelerate technological adoption across all segments of the manufacturing sector.

The assessment of organizational readiness examined management support, strategic planning, and innovation culture within manufacturing organizations. The results suggest that organizational factors play a critical role in determining the success of autonomous manufacturing implementation. Management support was found to be relatively strong among larger organizations. Senior executives increasingly recognize the strategic importance of digital transformation and are willing to allocate resources toward automation and technology development initiatives. Many

respondents reported that top management actively promotes innovation and supports investments in digital technologies. However, some SMEs indicated that management priorities remain focused on short-term operational concerns rather than long-term technological transformation.

Strategic planning emerged as another important factor influencing readiness. Organizations with formal digital transformation roadmaps demonstrated higher readiness levels than those lacking clear implementation strategies. Companies that established long-term objectives related to automation, data management, and technological integration were generally more prepared for autonomous manufacturing adoption. Nevertheless, a significant number of organizations, particularly smaller enterprises, reported the absence of comprehensive strategic plans for advanced manufacturing technologies.

The findings also revealed differences in organizational innovation culture. Large firms generally fostered environments that encourage experimentation, continuous improvement, and technological innovation. Employees in these organizations were more likely to participate in innovation projects and digital transformation initiatives. Conversely, many SMEs exhibited relatively conservative organizational cultures characterized by resistance to change and limited innovation activities. Such conditions may slow the adoption of autonomous manufacturing systems and reduce organizational adaptability in rapidly changing industrial environments.

Human resource readiness represents a critical determinant of successful autonomous manufacturing implementation because advanced technologies require a skilled and adaptable workforce (Siegel et al., 1997). The findings indicate that workforce readiness remains one of the most challenging aspects of industrial transformation in Indonesia.

The assessment of workforce digital competence revealed moderate readiness levels across most organizations. Employees generally possess basic digital literacy skills and familiarity with conventional automation technologies. However, competencies related to artificial intelligence, machine learning, data analytics, robotics programming, and advanced manufacturing systems remain limited. This skills gap presents a significant challenge for organizations seeking to implement more sophisticated autonomous technologies.

Employee training programs have become increasingly common among manufacturing companies. Many respondents reported participating in digital transformation workshops, technical certification programs, and technology-related training initiatives. Large enterprises tend to invest more heavily in workforce development and continuous learning programs compared to SMEs. Despite these efforts, respondents emphasized that existing training programs often fail to meet the rapidly evolving demands of advanced manufacturing environments.

A major concern identified during the assessment was the shortage of qualified talent. Many organizations reported difficulties in recruiting professionals with expertise in artificial intelligence, industrial data analytics, cybersecurity, and smart manufacturing technologies. The limited availability of specialized talent increases competition among companies and may slow the pace of technological adoption. Consequently, strengthening education-industry collaboration and workforce development initiatives is essential to support future autonomous manufacturing implementation.

As manufacturing systems become increasingly interconnected and data-driven, cybersecurity readiness has emerged as a critical requirement for autonomous manufacturing environments. The assessment indicates that cybersecurity readiness among Indonesian manufacturing industries is moderate but requires substantial improvement.

Most large organizations have established basic cybersecurity infrastructures, including firewalls, network monitoring systems, access control mechanisms, and data backup procedures. Several companies have also implemented cybersecurity policies and conducted periodic security assessments to identify potential vulnerabilities. These measures contribute to the protection of operational systems and sensitive industrial information.

Despite these improvements, cybersecurity capabilities remain uneven across the manufacturing sector. Many SMEs reported limited investment in cybersecurity technologies and lacked dedicated information security personnel. Such limitations increase vulnerability to cyberattacks, data breaches, and operational disruptions.

Cyber risk awareness among respondents has improved considerably in recent years. Organizations increasingly recognize that cyber threats can directly affect production continuity,

financial performance, and organizational reputation. However, awareness levels vary among employees, and many organizations continue to face challenges related to cybersecurity training and incident response preparedness. These findings suggest that stronger cybersecurity strategies and greater investment in security infrastructure are necessary to support the transition toward autonomous manufacturing systems.

Regulatory readiness evaluates the extent to which government policies, regulations, and institutional support mechanisms facilitate autonomous manufacturing adoption. The findings indicate that government initiatives have played an important role in encouraging industrial digital transformation, although several challenges remain.

3.3 Readiness Level Classification

The first category, Very Low Readiness, represents organizations that are not prepared to adopt autonomous manufacturing systems. Companies within this category generally exhibit minimal levels of technological adoption and continue to rely heavily on manual production processes. Automation infrastructure is largely absent, digital technologies are rarely utilized, and organizational awareness regarding autonomous manufacturing remains limited. Furthermore, these organizations typically lack strategic digital transformation plans, specialized workforce competencies, cybersecurity capabilities, and sufficient investment resources. As a result, substantial organizational and technological development is required before autonomous manufacturing implementation can be considered feasible.

The second category, Low Readiness, describes organizations that have initiated preparation efforts but remain at the early stages of digital transformation. Companies within this level may have implemented basic automation technologies or digital management systems in selected operational areas. However, technology integration remains fragmented, and advanced solutions such as Artificial Intelligence (AI), Industrial Internet of Things (IIoT), Digital Twins, and Cyber-Physical Systems are largely absent. Organizational support for innovation exists but is often limited by financial constraints, inadequate technical expertise, and insufficient strategic planning. Consequently, while these organizations recognize the importance of digital transformation, significant improvements are necessary before autonomous manufacturing systems can be effectively adopted.

The third category, Moderate Readiness, represents organizations that are partially prepared for autonomous manufacturing implementation. This category characterizes the majority of Indonesian manufacturing firms included in the study. Companies at this level have adopted various Industry 4.0 technologies, including automation systems, sensor networks, enterprise digital platforms, and data management solutions (Frank et al., 2019). Organizational leadership generally supports technological innovation, and digital transformation initiatives have been incorporated into business strategies. Workforce digital competencies are developing through training programs and skills development initiatives. However, limitations remain regarding system integration, AI deployment, cybersecurity maturity, and availability of specialized talent. Although these organizations possess a solid foundation for autonomous manufacturing, further investments and strategic improvements are necessary to achieve higher readiness levels.

The fourth category, High Readiness, includes organizations that are considered ready for autonomous manufacturing adoption. Companies within this category demonstrate extensive implementation of advanced manufacturing technologies, including integrated automation systems, AI-powered analytics, IIoT-enabled monitoring platforms, and real-time production management systems. Organizational leadership actively promotes innovation, allocates substantial resources for technological development, and maintains comprehensive digital transformation roadmaps. Workforce capabilities are supported by continuous training programs and access to specialized expertise. Cybersecurity frameworks are well established, and organizations generally comply with relevant industry standards and regulations. Although some challenges may remain, these organizations possess the technological, organizational, and human resource capabilities necessary to implement autonomous manufacturing systems successfully.

The highest category, Very High Readiness, represents organizations that are highly prepared and capable of operating within fully autonomous manufacturing environments (Schumacher et al., 2016). Companies in this category exhibit advanced digital maturity

characterized by intelligent production systems, extensive AI utilization, highly interconnected IIoT infrastructures, Digital Twin technologies, autonomous decision-making capabilities, and comprehensive cybersecurity protection mechanisms. These organizations maintain strong innovation cultures, highly skilled workforces, and strategic partnerships that support continuous technological advancement. Furthermore, they possess the flexibility and resilience necessary to adapt to rapidly changing market demands and technological developments. Such organizations serve as benchmarks for industrial transformation and demonstrate the potential benefits of fully integrated autonomous manufacturing systems.

Based on the overall assessment, the majority of Indonesian manufacturing industries were classified within the Moderate Readiness category. While many organizations have made substantial progress in adopting Industry 4.0 technologies and developing digital capabilities, the transition toward fully autonomous manufacturing systems remains incomplete. Large enterprises generally achieved higher readiness classifications due to greater financial resources, advanced technological infrastructure, and stronger organizational support. In contrast, small and medium-sized enterprises (SMEs) were more frequently classified within the Low or Moderate Readiness categories because of limitations in investment capacity, workforce expertise, and technology adoption.

These findings indicate that Indonesia's manufacturing sector has established a promising foundation for autonomous manufacturing development but still faces several challenges that must be addressed. Enhancing technological capabilities, strengthening workforce competencies, improving cybersecurity preparedness, and expanding government support mechanisms will be critical for enabling organizations to progress from moderate readiness toward high and very high readiness levels. Ultimately, the readiness classification framework provides valuable insights for policymakers, industry leaders, and technology providers seeking to accelerate Indonesia's transition toward intelligent and autonomous manufacturing systems.

3.4 Comparison of Findings with Previous Studies

The findings of this study generally align with previous research on Industry 4.0 readiness and digital transformation within manufacturing industries, while also providing new insights into the preparedness of Indonesian industries for Autonomous Manufacturing Systems (AMS). The overall assessment revealed that Indonesian manufacturing industries demonstrate a moderate level of readiness for autonomous manufacturing adoption. This finding is consistent with earlier studies that reported ongoing progress in industrial digitalization but highlighted significant challenges related to technology adoption, workforce development, and organizational transformation.

The results support the findings of Simamora et al. (2020), who concluded that Indonesia's manufacturing sector is progressing toward Industry 4.0 implementation but still faces substantial obstacles in terms of technological capability, innovation capacity, and human resource development. Similar to their study, the present research found that larger manufacturing firms generally possess stronger technological infrastructures and greater readiness for advanced manufacturing technologies than small and medium-sized enterprises (SMEs). Both studies indicate that disparities in financial resources and technological investment significantly influence industrial readiness levels (Glenn Richey Jr & Autry, 2009).

The findings also correspond with the maturity assessment framework proposed by Almamalik (2020), which emphasized the importance of evaluating readiness across multiple dimensions, including technology, organization, and operations. In the current study, technological readiness emerged as one of the strongest dimensions among large manufacturing firms, particularly regarding automation adoption and digital infrastructure. However, similar to Almamalik's conclusions, significant gaps remain in the integration of advanced technologies such as Artificial Intelligence (AI), Digital Twins, and Cyber-Physical Systems, particularly among SMEs.

The technological readiness results are further supported by the systematic literature review conducted by Hizam-Hanafiah, Soomro, and Abdullah (2020). Their study identified technology, organizational culture, leadership, and workforce competency as critical readiness dimensions for Industry 4.0 implementation. The present research confirms the importance of these factors and demonstrates that technological readiness alone is insufficient for successful autonomous manufacturing adoption. Instead, organizations require strong leadership commitment, strategic

planning, workforce capabilities, and supportive organizational cultures to fully realize the benefits of advanced manufacturing technologies.

Regarding organizational readiness, the findings reinforce previous studies highlighting the role of management support and innovation culture in digital transformation success (Zhen et al., 2021). The current research found that organizations with clearly defined digital transformation strategies and strong executive commitment exhibited higher readiness levels. This observation is consistent with Ginting and Zagloel (2023), who identified leadership commitment, organizational strategy, and investment capability as among the most influential factors affecting Industry 4.0 adoption. Both studies suggest that technological investments must be accompanied by organizational change initiatives and long-term strategic planning to achieve sustainable transformation.

The human resource readiness findings are also largely consistent with previous research. Similar to the conclusions of Krupitzer et al. (2020), this study found that workforce competency remains one of the most significant barriers to advanced manufacturing implementation. While employees generally possess basic digital skills, there is a shortage of expertise in artificial intelligence, data analytics, robotics programming, and autonomous system management. This shortage of specialized talent continues to limit the pace of digital transformation and highlights the need for enhanced workforce development programs. The findings further support earlier studies emphasizing that successful implementation of intelligent manufacturing systems requires continuous employee training and strong collaboration between industry and educational institutions.

In terms of cybersecurity readiness, the results indicate moderate preparedness across the manufacturing sector. While larger firms have invested in security infrastructure and risk management practices, many SMEs remain vulnerable to cyber threats due to limited resources and expertise. These findings align with recent Industry 4.0 readiness studies, which identify cybersecurity as a growing concern in increasingly interconnected manufacturing environments. The dependence of autonomous manufacturing systems on real-time data exchange and network connectivity makes cybersecurity a critical prerequisite for successful implementation.

The study's findings regarding regulatory readiness also correspond with previous Indonesian research. Hasbullah and Bareduan (2023) argued that existing readiness assessment frameworks and policy support mechanisms require further refinement to effectively support industrial transformation. Similarly, respondents in the current study generally viewed government initiatives positively, particularly the Making Indonesia 4.0 roadmap and smart factory development programs. However, many organizations expressed concerns regarding policy implementation, accessibility of support programs, and the lack of comprehensive standards governing autonomous manufacturing technologies. These findings suggest that while policy frameworks have created a favorable environment for digital transformation, additional efforts are needed to strengthen regulatory support and facilitate broader technology adoption.

Despite these similarities, the present study extends previous research in several important ways (González, 2011). Most existing studies focus on Industry 4.0 adoption, digital transformation readiness, or smart manufacturing maturity. In contrast, this research specifically evaluates readiness for Autonomous Manufacturing Systems, which represent a more advanced stage of industrial evolution characterized by intelligent decision-making, self-optimization, and minimal human intervention. By incorporating technological, organizational, human resource, cybersecurity, and regulatory dimensions into a single assessment framework, this study provides a more comprehensive understanding of the factors influencing autonomous manufacturing adoption in Indonesia.

Another significant contribution of this research is the identification of readiness disparities between large enterprises and SMEs. While previous studies have acknowledged these differences, the current findings demonstrate that the readiness gap becomes even more pronounced when evaluating technologies associated with autonomous manufacturing. Large enterprises are generally classified within the High Readiness category, whereas many SMEs remain within the Low or Moderate Readiness categories. This finding suggests that future policy interventions should place greater emphasis on supporting SME digital transformation through financial incentives, technical assistance, workforce development programs, and technology access initiatives.

4. CONCLUSION

This study examined the readiness of Indonesian manufacturing industries for the adoption of Autonomous Manufacturing Systems (AMS) by evaluating technological, organizational, human resource, cybersecurity, and regulatory dimensions. The findings indicate that the overall readiness level of Indonesian manufacturing industries can be classified as moderate, suggesting that many organizations have established a foundation for digital transformation but are not yet fully prepared for widespread autonomous manufacturing implementation. Technological readiness and organizational readiness emerged as the strongest dimensions, particularly among large manufacturing firms that have invested in automation, digital infrastructure, and strategic transformation initiatives. In contrast, human resource readiness and cybersecurity readiness were identified as the weakest dimensions due to persistent shortages of specialized talent, limited AI-related competencies, insufficient workforce training, and uneven cybersecurity capabilities, especially among small and medium-sized enterprises (SMEs). The study confirms that Indonesian industries are partially prepared to adopt autonomous manufacturing systems, with readiness being influenced by factors such as technology infrastructure, leadership commitment, innovation culture, workforce competencies, cybersecurity preparedness, financial resources, and regulatory support. Based on these findings, manufacturing firms are encouraged to accelerate investments in advanced technologies, workforce development, and integrated digital transformation strategies. Government agencies should strengthen support programs, facilitate technology adoption, and create a more conducive regulatory environment, while educational institutions should enhance industry-oriented curricula and training programs related to artificial intelligence, automation, robotics, data analytics, and smart manufacturing technologies. Policy recommendations include increasing AI workforce training initiatives, expanding digitalization support for SMEs, strengthening national cybersecurity standards, promoting industry-academia collaboration, and extending incentives for smart factory development. Despite its contributions, this study has several limitations, including its focus on selected manufacturing sectors, a limited sample size, and a concentration of respondents in major industrial regions, which may affect the generalizability of the findings. Therefore, future research should investigate AI adoption among SMEs, conduct smart factory maturity assessments, develop in-depth case studies of autonomous manufacturing implementation, and perform comparative analyses across Southeast Asian countries to provide broader insights into regional industrial transformation and competitiveness.

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