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The Integration of AI and IoT in Cyber-Physical Systems for Smart Manufacturing in Indonesia

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ABSTRACT

The integration of Artificial Intelligence (AI) and the Internet of Things (IoT) within Cyber-Physical Systems (CPS) represents a transformative opportunity for smart manufacturing in Indonesia. This study employs a qualitative approach, with insights from five informants, to explore the current state, challenges, opportunities, and strategic recommendations for CPS adoption. Findings reveal that while CPS adoption is in its early stages, it has significant potential to enhance operational efficiency, sustainability, and global competitiveness. Challenges such as limited infrastructure, skill gaps, and cybersecurity concerns are prevalent. However, opportunities exist in leveraging government initiatives, fostering local innovation, and promoting sustainability. Strategic recommendations include enhancing digital infrastructure, providing financial incentives, upskilling the workforce, and establishing clear regulatory frameworks. These insights contribute to advancing Indonesia's Industry 4.0 agenda and offer a roadmap for stakeholders to navigate CPS integration effectively.

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1. INTRODUCTION

The rapid advancement of technology has transformed the global manufacturing landscape, with the integration of Artificial Intelligence (AI) and the Internet of Things (IoT) in Cyber-Physical Systems (CPS) becoming central to the Fourth Industrial Revolution (Industry 4.0). Smart manufacturing, a key component of Industry 4.0, utilizes AI and IoT for real-time monitoring, predictive maintenance, and automated decision-making to boost productivity, efficiency, and sustainability. In Indonesia—one of Southeast Asia's largest emerging economies—these innovations present significant opportunities for industrial modernization. The combination of AI and IoT supports real-time data exchange, predictive capabilities, and intelligent decision-making to optimize processes and resource use [1]. IoT sensors improve predictive maintenance and quality control,

while AI-driven analytics enhance decision-making and performance [1]. Technologies like CPS, Big Data, and robotics further enable flexible, efficient, and customized manufacturing, helping transition from traditional to service-oriented business models [2]. For Indonesia, adopting these technologies could strengthen global competitiveness and align with evolving industrial trends [3]. However, success also depends on overcoming key challenges such as cybersecurity, skills gaps, and regulatory compliance [4].

The Indonesian manufacturing sector, which plays a vital role in contributing to the country's Gross Domestic Product (GDP) and employment, faces growing pressure to adopt innovative technologies in order to remain competitive globally. The integration of Artificial Intelligence (AI) and the Internet of Things (IoT) within Cyber-Physical Systems (CPS) is a crucial step in this transformation but comes with significant challenges, including infrastructure limitations, a shortage of technological expertise, and regulatory barriers. To address these issues, the government has launched strategic initiatives such as "Making Indonesia 4.0," aimed at positioning the country as a global leader in manufacturing by embracing Industry 4.0 technologies. Despite the promise of such digitalization, gaps remain in technology adoption and workforce skills, as highlighted by assessments of Indonesia's industrial readiness [5]. The high cost of investment and the need for major infrastructure upgrades further complicate implementation efforts [6]. Nevertheless, the government continues to promote cross-sector collaboration through its policy initiatives, encouraging partnerships among public institutions, private enterprises, and academia to accelerate industrial transformation [5]. Special focus on small and medium enterprises (SMEs) within sectors like electronics and machinery illustrates the policy drive to enhance competitiveness and foster innovation [7]. Industry 4.0 also brings opportunities for automation, connectivity, and market expansion, enabling more efficient production while responding to demands for product customization and environmental sustainability [8], [9].

The integration of Artificial Intelligence (AI) and the Internet of Things (IoT) into Cyber-Physical Systems (CPS) has become a hallmark of the modern manufacturing landscape, offering unprecedented opportunities for efficiency, scalability, and innovation; however, the adoption of these technologies in developing economies such as Indonesia remains constrained by several challenges. Limited infrastructure, a shortage of skilled labor, and inadequate regulatory frameworks hinder the seamless implementation of AI and IoT in smart manufacturing, while many Indonesian manufacturers struggle to align advanced technological solutions with existing industrial practices, creating a gap between potential benefits and actual outcomes. Despite government-led initiatives like "Making Indonesia 4.0," which aim to digitize the manufacturing sector, numerous businesses face difficulties related to cost, interoperability, and cybersecurity. These issues are further complicated by Indonesia's diverse industrial landscape, where levels of digital readiness vary significantly across regions and sectors. Without targeted strategies and data-driven insights, the promise of smart manufacturing in Indonesia risks going unrealized, potentially hampering national industrial competitiveness and long-term economic growth.

This study aims to investigate the integration of Artificial Intelligence (AI) and the Internet of Things (IoT) in Cyber-Physical Systems (CPS) for smart manufacturing in Indonesia, with several key objectives: to analyze the current state of AI and IoT adoption in Indonesian manufacturing industries and identify the main technological and organizational barriers; to explore the perspectives and experiences of industry experts, policymakers, and technology specialists regarding CPS implementation within the Indonesian context; to identify opportunities for fostering the adoption of AI and IoT in CPS by addressing infrastructural, skill-related, and regulatory challenges; and

to provide actionable recommendations that support the digital transformation of Indonesia's manufacturing sector in alignment with the strategic goals of the "Making Indonesia 4.0" initiative.

2. LITERATURE REVIEW

2.1. Theoretical Foundations of AI and IoT in CPS

The integration of Artificial Intelligence (AI) and the Internet of Things (IoT) within Cyber-Physical Systems (CPS) is crucial for advancing intelligent manufacturing ecosystems. AI offers advanced analytics, machine learning, and predictive capabilities, enabling CPS to learn from data and improve over time, while IoT ensures seamless connectivity among devices and sensors for efficient data exchange. Together, AI and IoT foster automation, optimization, and adaptability in manufacturing. The Industrial Internet Reference Architecture (IIRA) highlights the importance of these technologies in enabling real-time communication and data-driven decision-making across organizational levels [10]. Machine learning enhances CPS functions such as analysis, control, and decision-making, while also addressing security risks through threat detection [11], [12]. IoT supports data collection and real-time analytics, improving responsiveness and efficiency, particularly when combined with edge computing to reduce latency [13]. Looking forward, innovations like edge AI, fog computing, and blockchain are expected to further strengthen CPS capabilities in smart manufacturing [13].

2.2. Global Trends in Smart Manufacturing

Smart manufacturing, powered by AI and IoT technologies, has advanced significantly worldwide, with countries like Germany, Japan, and the United States leading the adoption of Industry 4.0 to boost productivity, reduce costs, and support product customization. Key applications such as predictive maintenance and digital twins are central to optimizing processes—AI analyzes IoT sensor data to anticipate equipment failures, minimizing downtime and costs [14]. Digital twins enable performance simulations, while IoT-based energy monitoring and AI optimization contribute to sustainability by cutting energy use and supporting circular practices [14]. Globally, Germany's Industrie 4.0 has influenced manufacturing policy, the U.S. has developed adaptive smart systems, and Japan emphasizes AI-IoT integration for efficiency [2]. AI and IoT serve as core enablers, offering connectivity, data analysis, and intelligent decision-making [14], while Cyber-Physical Systems (CPS) support flexible, efficient operations and innovative business models [2].

2.3. Challenges and Opportunities in the Indonesian Context

Indonesia's manufacturing sector faces major challenges in adopting Cyber-Physical Systems (CPS) technologies due to infrastructure limitations, a shortage of skilled personnel, and regulatory uncertainties. Inadequate broadband coverage and high electricity costs impede IoT implementation, while effective CPS deployment requires robust interconnectivity and computing platforms [8]. Only 6% of the industry is considered competent in AI adoption, reflecting a lack of awareness and technical readiness [15]. This skills gap hinders the development and maintenance of CPS solutions. Additionally, regulatory and cybersecurity concerns—such as data security, access protocols, and data quality—

pose further obstacles [16]. Nevertheless, the "Making Indonesia 4.0" initiative offers a strategic roadmap to address these issues, focusing on priority sectors like food and beverage, textiles, automotive, electronics, and chemicals. It promotes public-private partnerships, education and training, and the development of local innovation ecosystems to drive Industry 4.0 adoption and support IoT-based start-ups [17].

3. RESEARCH METHODOLOGY

3.1. Research Design

This study adopts a qualitative research design to provide an in-depth understanding of the challenges, opportunities, and strategies related to the integration of AI and IoT in Cyber-Physical Systems (CPS), enabling a rich exploration of the socio-technical dynamics, stakeholder perceptions, and organizational contexts that shape smart manufacturing practices in Indonesia. As an exploratory study, it focuses on uncovering patterns and insights rather than testing predefined hypotheses, aiming to construct a comprehensive understanding of CPS adoption within the Indonesian industrial landscape by examining the perspectives of diverse informants.

3.2. Informants and Sampling

The study involved five key informants selected through purposive sampling to capture diverse perspectives aligned with the research objectives. The informants included industry experts with experience in implementing AI and IoT in manufacturing, policymakers from governmental bodies involved in industrial digitalization initiatives, and technology specialists in AI, IoT, and CPS development. Selection criteria focused on individuals directly engaged in smart manufacturing initiatives or policymaking, ensuring the relevance and depth of insights. This approach enabled a nuanced understanding of the specific challenges and opportunities facing Indonesia's manufacturing sector.

3.3. Data Collection

Data were collected through semi-structured interviews with the selected informants, guided by open-ended questions that explored the current state of AI and IoT integration in CPS, perceived challenges and barriers to implementation, opportunities and strategic initiatives for fostering CPS adoption, and the role of government policies and private sector collaboration in enabling smart manufacturing. Each interview lasted between 60 to 90 minutes and was conducted either in-person or via video conferencing, depending on the informants' availability. With their consent, all interviews were recorded and transcribed verbatim for analysis.

3.4. Data Analysis

Thematic analysis was employed to analyze the interview data, following a structured process that included familiarization through repeated reading of transcripts to identify initial impressions, coding relevant data segments related to the research questions—such as "infrastructure challenges," "policy gaps," and "training needs"—and developing broader themes like "technological readiness" and "stakeholder collaboration" to capture key insights. These themes were then interpreted to construct a coherent narrative aligned with the research objectives. NVivo software was used to manage and code the data, ensuring a systematic and rigorous analysis process.

4. RESULTS AND DISCUSSION

4.1. Current State of AI and IoT Adoption

The integration of Artificial Intelligence (AI) and the Internet of Things (IoT) into Cyber-Physical Systems (CPS) has garnered significant attention in advancing smart manufacturing in Indonesia. Findings from interviews with key informants reveal varying levels of awareness, adoption trends, regional disparities, and implementation challenges across industries. While all informants recognized the transformative potential of AI and IoT, awareness is notably higher among large corporations compared to small and medium-sized enterprises (SMEs). As noted by Informant 1, a senior manager from an electronics firm, "We see AI and IoT as essential for staying competitive in the global market. Predictive maintenance and real-time monitoring have already reduced our downtime by 30%." In contrast, Informant 3, a textile manufacturer, admitted, "We've heard about IoT but don't fully understand how it can be applied to our processes. We are still focused on manual operations."

Adoption levels vary significantly across sectors. Industries such as electronics and automotive are leading in CPS adoption, using AI-driven automation and IoT-enabled analytics to enhance productivity. Informant 2, an automotive supplier, shared, "Our assembly lines are equipped with IoT sensors that allow us to monitor efficiency in real time. This has led to a 15% increase in output." Meanwhile, traditional sectors like agriculture and food processing lag behind due to limited resources and reliance on legacy systems. Informant 5, a food processing business owner, remarked, "Investing in new technology seems risky for us. Our margins are tight, and we're unsure about the returns." Regional disparities further complicate adoption, with urban centers like Jakarta and Surabaya emerging as innovation hubs due to better infrastructure, while rural areas struggle with basic connectivity. As Informant 4, based in a rural area, stated, "Internet connectivity here is unreliable, making it difficult to even consider IoT solutions. We need government support to improve infrastructure."

The maturity of Indonesia's technological ecosystem also differs between large firms and emerging startups. Multinational corporations have made significant investments in CPS and often collaborate with international technology providers. Informant 1 explained, "Our company collaborates with international technology providers to stay ahead. The partnerships bring in not just technology but also expertise." In contrast, local startups are creating affordable, localized CPS solutions but face challenges in scaling and earning industry trust. Informant 3 observed, "Local startups provide affordable CPS options, but many SMEs lack the confidence to adopt them due to insufficient proof of success." Despite the enthusiasm for CPS, informants identified persistent gaps in technological readiness and implementation. Infrastructure remains a core issue—"Without reliable power and connectivity, deploying IoT devices becomes a challenge," said Informant 4. Additionally, skill shortages hinder effective implementation, as emphasized by Informant 2: "Training employees to use these technologies effectively takes time, and not everyone adapts quickly."

4.2. *Challenges in CPS Integration*

Despite the significant potential of Cyber-Physical Systems (CPS) to revolutionize manufacturing in Indonesia, this study identified numerous challenges that hinder the effective integration of AI and IoT technologies. These challenges span technical, organizational, economic, and policy-related dimensions. A key issue is the inadequacy of digital infrastructure, particularly in rural areas, where unreliable internet and inconsistent power supply disrupt CPS operations. As Informant 4, a manufacturer from a rural region, explained, "Our factory's internet connection is unstable, making it nearly impossible to run IoT systems efficiently." System interoperability is another hurdle, especially for firms using legacy equipment. Informant 2, an automotive supplier, noted, "We have older machines that are incompatible with modern IoT sensors, making retrofitting expensive and complicated." Organizational resistance to change also persists, with employees often hesitant to adopt new technologies due to fear of job displacement. "Our workers are hesitant about using automated systems. They fear job losses and are uncomfortable with the technology," said Informant 3. Furthermore, skill gaps remain a major constraint, as companies lack staff with the technical expertise needed to manage CPS. Informant 5 stated, "We don't have staff who are trained in managing IoT systems or analyzing AI-driven data."

Economic and policy-related barriers further complicate CPS integration. High initial investment costs deter many firms, particularly SMEs, from adopting IoT devices and AI platforms. "The initial investment for IoT sensors and AI platforms is high, which can be a barrier even for medium-sized companies," said Informant 1. In addition, unclear returns on investment (ROI) create hesitation among manufacturers. Informant 5 shared, "We need clearer data on how much CPS will improve productivity and profitability before committing resources." The lack of standardized implementation protocols adds to the uncertainty, with Informant 2 pointing out, "Without clear standards, we are unsure if our systems will align with future regulations or be compatible with other networks." Informants also expressed concern over insufficient government support, calling for more tangible assistance like infrastructure funding, tax incentives, or grants. "We need more government assistance, especially in upgrading infrastructure and providing financial aid to smaller companies," remarked Informant 4. Additionally, the digital nature of CPS increases exposure to cyber threats, prompting further investment in security. As Informant 1 emphasized, "As we integrate IoT devices, cybersecurity becomes a priority, but it also adds another layer of cost and complexity."

4.3. *Opportunities for CPS Adoption*

Despite various challenges, there are substantial opportunities for adopting Cyber-Physical Systems (CPS) in Indonesia's smart manufacturing sector, driven by economic growth, supportive government policies, and advancing technologies. The country's expanding industrial base increases demand for automation and digitalization to enhance efficiency. Informant 1, a senior manager in electronics, stated, "With the growing middle class and export demands, adopting CPS can help us scale production while maintaining quality." Government initiatives

under "Making Indonesia 4.0" offer infrastructure support, technology subsidies, and training programs to accelerate CPS adoption. As Informant 4, a rural factory owner, noted, "Government-backed training programs are introducing our workforce to digital tools, which will make it easier to adopt CPS technologies." Tax incentives and public-private collaboration further strengthen the ecosystem.

The decreasing cost of IoT devices, cloud computing, and AI platforms makes CPS more accessible, especially for SMEs. Informant 3 shared, "We've started working with a local tech startup to pilot IoT sensors on a small scale. This approach is cost-effective and aligns with our needs." CPS also supports sustainable manufacturing by reducing energy use and waste, which enhances global competitiveness. Informant 2 explained, "Our IoT-enabled production lines help monitor energy usage in real time, reducing electricity costs by 20%." Workforce upskilling efforts are empowering employees to adapt to new technologies, as highlighted by Informant 5: "Our younger employees are eager to learn about IoT and AI tools." These developments position Indonesian manufacturers to better meet international standards and integrate more fully into global supply chains.

4.4. Strategic Recommendations

Based on the study's findings, several strategic recommendations are proposed to accelerate CPS integration in Indonesia's manufacturing sector. Strengthening digital infrastructure is critical, especially in rural and industrial areas, to support reliable internet and power access. Informant 4 noted, "Government and private partnerships in upgrading internet services will benefit remote manufacturers like us." Workforce development is also essential, with training and certification programs needed to close the skills gap. "Continuous learning programs are necessary for employees to stay relevant in a digitalized work environment," said Informant 5. Supporting local innovation through R&D grants and partnerships with startups can lower costs and provide tailored CPS solutions. Informant 3 shared, "Collaborating with local startups on IoT integration has been both affordable and practical for us." Financial incentives, such as subsidies and tax breaks, can ease the burden of high initial investments, as emphasized by Informant 1: "Tax incentives for purchasing IoT equipment would encourage more companies to invest in these technologies."

Clear regulatory frameworks are needed to ensure consistency and cybersecurity in CPS deployment. "Having clear standards will simplify implementation and ensure future compatibility," stated Informant 2. Promoting sustainability through energy-efficient CPS solutions aligns with global environmental goals. Informant 2 shared, "Using IoT for energy monitoring has helped us lower emissions and reduce costs." Enhancing collaboration and knowledge sharing via industry forums can accelerate learning and adoption, as Informant 1 suggested, "Learning from peers who have successfully implemented CPS can significantly reduce our learning curve." Finally, stronger government advocacy and the integration of CPS into national policy will build confidence among manufacturers. Informant 4 remarked, "Government advocacy for digital transformation

will instill confidence in smaller manufacturers to adopt CPS."

4.5. Discussion

The integration of Cyber-Physical Systems (CPS) in smart manufacturing marks a crucial step for Indonesia in aligning with global Industry 4.0 initiatives. This study provides a comprehensive overview of the current state, challenges, opportunities, and strategic directions for CPS adoption within the Indonesian manufacturing sector. Although CPS adoption remains in its early stages, there is increasing awareness of its potential to transform industrial operations. The use of Artificial Intelligence (AI) and the Internet of Things (IoT) has proven effective in automating workflows, enhancing operational efficiency, and supporting data-driven decision-making. However, several barriers persist, including infrastructure limitations, skill shortages, high implementation costs, and cybersecurity risks, which collectively slow the pace of adoption.

These challenges point to the urgent need for targeted strategies to address structural limitations such as underdeveloped digital infrastructure and the financial barriers faced by small and medium enterprises (SMEs). On the other hand, the study identifies promising opportunities for Indonesia to harness CPS in driving economic growth, sustainability, and global competitiveness. Government efforts, particularly through the "Making Indonesia 4.0" roadmap, provide a solid policy foundation for accelerating CPS integration. This includes initiatives such as fiscal incentives, vocational training programs, and infrastructure development aimed at creating an enabling environment for smart manufacturing. With continued collaboration among stakeholders, Indonesia is well-positioned to transition toward a more innovative and resilient industrial future.

The study aligns with global research on Cyber-Physical Systems (CPS) integration, emphasizing the critical roles of infrastructure readiness, skill development, and regulatory frameworks. While developed nations have made significant strides in CPS adoption, Indonesia's progress is shaped by unique contextual challenges such as uneven infrastructure and a shortage of local technological expertise. These limitations hinder the seamless implementation of Industry 4.0 and 5.0 technologies, especially in rural and underdeveloped regions [18], [19]. However, the research highlights promising developments, including an expanding ecosystem of local startups and proactive government initiatives that are gradually bridging these gaps. These efforts, through public-private collaboration and policy support, are crucial for positioning Indonesia to align more closely with global trends [19], [20].

Moreover, the study underscores the importance of sustainability in CPS adoption, which resonates with international priorities for promoting eco-friendly manufacturing practices. Informants consistently emphasized the positive impact of IoT technologies on improving energy efficiency and reducing waste, reaffirming CPS's potential in supporting environmental objectives [7], [21]. Government strategies and startup innovations are contributing to more energy-conscious production methods, aligning Indonesia's manufacturing transformation with global sustainability goals. As the country continues to develop its digital and industrial infrastructure,

these initiatives represent essential steps toward building a resilient, inclusive, and environmentally responsible smart manufacturing ecosystem.

4.6. Implications for Policy and Practice

The findings underline the critical role of government policies in creating an enabling environment for CPS adoption. Policies should focus on incentivizing investments in AI and IoT technologies, enhancing cybersecurity measures, and establishing standardized guidelines for CPS integration. The role of public-private partnerships is also pivotal in addressing infrastructure challenges and fostering innovation.

For practitioners, the study suggests a phased approach to CPS adoption, starting with low-cost pilot projects to build familiarity and confidence among stakeholders. Collaboration with technology providers, both local and international, can bridge knowledge gaps and reduce implementation costs. Moreover, continuous workforce training and development are essential to ensure that employees are equipped to handle advanced CPS technologies.

4.7. Contribution to Industry 4.0 Objectives

The findings contribute to Indonesia's Industry 4.0 objectives by identifying actionable strategies for CPS integration. By addressing the identified challenges and leveraging the outlined opportunities, the manufacturing sector can enhance productivity, reduce operational costs, and meet global standards. Furthermore, the emphasis on sustainability aligns with Indonesia's commitments to international environmental agreements, positioning the country as a responsible global manufacturing hub.

4.8. Limitations and Future Research

While this study provides valuable insights, it is limited by its qualitative nature and the small sample size of five informants. Future research could expand the sample size and incorporate quantitative methods to validate the findings. Additionally, exploring sector-specific challenges and opportunities in greater detail would offer more tailored recommendations for CPS adoption.

5. CONCLUSION

This study highlights the transformative potential of CPS integration in Indonesia's manufacturing sector, emphasizing its role in advancing Industry 4.0 objectives. Despite significant challenges, such as inadequate infrastructure, skill shortages, and cybersecurity risks, the opportunities for growth and innovation are immense. Strategic measures, including enhanced digital infrastructure, targeted workforce training, financial incentives, and clear regulatory support, are essential for overcoming these barriers. By implementing these strategies, Indonesia can capitalize on CPS technologies to boost operational efficiency, foster sustainability, and position itself as a competitive player in the global manufacturing landscape. Future efforts should focus on addressing regional disparities, fostering public-private partnerships, and promoting sector-specific CPS applications to ensure a comprehensive and inclusive transition to smart manufacturing.

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