

TOWARDS INDUSTRY 5.0; A HUMAN-CENTRIC CYBER-PHYSICAL PRODUCTION SYSTEM FOR INDONESIA'S BATIK SMES

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Abstract

Industry 4.0 has revolutionized manufacturing through automation and data exchange, but the transition towards Industry 5.0 emphasizes human-centric approaches, integrating human expertise with advanced technologies like cyber-physical systems (CPS). In Indonesia, Small and Medium Enterprises (SMEs), particularly in traditional sectors such as batik production, face challenges in adapting to these technological advancements. The batik industry, while rich in cultural heritage, has yet to fully embrace automation or digitalization, resulting in inefficiencies and limited scalability. This study aims to explore the potential of Industry 5.0 by developing a human-centric cyber-physical production system (HCPPS) tailored to Indonesia's batik SMEs. The goal is to enhance production efficiency while preserving traditional craftsmanship through the integration of smart technologies. The research employed a mixed-methods approach, combining qualitative interviews with batik producers and quantitative analysis using data from pilot implementations of a CPS model. A prototype of a human-centric cyber-physical system was developed, integrating Internet of Things (IoT) devices, augmented reality (AR), and robotics to assist batik artisans. The implementation of the HCPPS prototype resulted in a 25% increase in production efficiency, while artisans reported higher job satisfaction due to enhanced skill integration with technology. The system enabled greater customization, faster production cycles, and reduced errors. The study demonstrates that Industry 5.0's human-centric approach can significantly improve productivity in traditional sectors like batik, providing a path for Indonesian SMEs to modernize while maintaining their cultural identity.

Keywords: Batik SMEs, Cyber-Physical Systems, Human-Centric Production



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INTRODUCTION

The manufacturing landscape has undergone a significant transformation with the advent of Industry 4.0, which is characterized by automation, data exchange, and cyber-physical systems (CPS). This shift has redefined how industries operate, emphasizing efficiency, flexibility, and customization. However, as the world transitions towards Industry 5.0, the focus is increasingly on creating human-centric systems that combine advanced technologies with human intelligence and creativity (Alves et al., 2025). Industry 5.0 is seen as a future where human expertise and machine capabilities work collaboratively, enhancing not only productivity but also job satisfaction and creativity (Amaral et al., 2025). In Indonesia, Small and Medium Enterprises (SMEs), especially in the traditional sectors such as batik production, face numerous challenges in adopting these advancements (Antomarioni et al., 2025). The batik industry, which has long been a cornerstone of Indonesia's cultural heritage, still relies heavily on manual processes, making it difficult to scale production efficiently while preserving the craftsmanship that defines this art form (Aruväli et al., 2025). Despite the introduction of new technologies, such as automation and digital tools in manufacturing, the batik industry remains largely disconnected from these advancements. Batik, a traditional form of textile art in Indonesia, faces particular challenges in adopting Industry 4.0 innovations due to its intricate production methods, labor-intensive processes, and the need for skilled artisans (Atay et al., 2025). The traditional methods employed by batik artisans have limited scalability, slow production cycles, and high rates of errors. While larger industries have successfully integrated smart technologies like robotics and Internet of Things (IoT) devices, the batik sector has largely remained untouched by these developments (Barrero-Arciniegas et al., 2025). The integration of cyber-physical systems, tailored to the specific needs of this traditional sector, has the potential to bridge the gap between heritage and modernity. Thus, Industry 5.0 presents an opportunity to modernize batik production while maintaining its artistic and cultural significance (Bécue et al., 2025).

As the global trend toward Industry 5.0 gains momentum, understanding its implications for traditional industries like batik becomes crucial for fostering sustainable growth and innovation in Indonesia. This research aims to explore how the principles of Industry 5.0 can be applied to the batik sector, enabling SMEs to enhance their production processes and remain competitive in an increasingly digitalized world (Bittencourt et al., 2025). The human-centric approach of Industry 5.0 offers the possibility of a harmonious blend of technology and tradition, which could not only improve operational efficiency but also create more meaningful roles for workers in the production process (Bolis et al., 2025). This study aims to investigate the potential benefits and challenges of such an integration, with a specific focus on batik SMEs in Indonesia (Bongomin et al., 2025). The primary issue addressed in this study is the lack of integration between traditional batik production processes and modern technological advancements, particularly those associated with Industry 4.0 and Industry 5.0 (Brückner et al., 2025). While batik SMEs continue to play a vital role in Indonesia's economy and cultural heritage, their productivity remains limited by the reliance on manual labor and outdated techniques. These traditional methods hinder the scalability of production and often result in inefficiencies and errors, especially during peak demand periods (Callari et al., 2025).

The introduction of automation, data exchange, and cyber-physical systems could significantly improve the efficiency and accuracy of batik production. However, these technologies have not been widely adopted within the batik industry due to several factors, including the complexity of traditional processes, the need for skilled artisans, and a lack of

infrastructure and awareness within SMEs (Callari et al., 2025). The specific problem that this study addresses is the challenge of modernizing batik production without sacrificing the artisanal value and cultural integrity of the craft (Chen et al., 2025). While larger industries have embraced Industry 4.0 technologies, smaller-scale batik producers have been slow to adopt these innovations due to financial constraints, lack of technical knowledge, and the deeply embedded nature of traditional practices. Industry 5.0, with its focus on human-centered technology, offers a promising solution by enabling technology to complement and enhance human skills rather than replace them (Chrifi-Alaoui et al., 2025). This study aims to explore how a human-centric cyber-physical production system can be implemented in Indonesia's batik SMEs, balancing the need for technological advancement with the preservation of traditional craftsmanship.

The research seeks to answer how Industry 5.0 can be effectively applied to batik production, particularly in the context of Indonesia's SMEs. By focusing on human-centric cyber-physical systems, the study will explore how technology can support artisans in improving productivity, reducing errors, and increasing customization in batik production. The goal is to identify practical, scalable solutions that allow batik SMEs to integrate modern technology while preserving the cultural significance of their work (Ciampi et al., 2025). The research will also examine the barriers and challenges that may arise in the adoption of such systems, as well as the potential impacts on the workforce and local communities. The primary objective of this research is to design and implement a human-centric cyber-physical production system (HCPPS) tailored to the needs of batik SMEs in Indonesia (Cimino et al., 2025). The aim is to enhance production efficiency, reduce errors, and enable greater customization of batik products, while preserving the cultural and artistic integrity of the craft. This study will focus on the integration of smart technologies, such as Internet of Things (IoT) devices, robotics, and augmented reality (AR), into the traditional batik production process. By developing a prototype HCPPS, the research will assess the potential of these technologies to improve productivity and quality control in batik manufacturing, while maintaining the human expertise that is central to the craft (da Silva et al., 2026).

In addition to exploring the technological integration, the research aims to evaluate the impact of the proposed system on the artisans and workers within batik SMEs (De Marchi et al., 2025). This includes assessing how the HCPPS influences job satisfaction, skill development, and the overall work environment. The study also seeks to identify the challenges and opportunities for adopting such a system, with a particular focus on the feasibility of scaling these solutions to a wider range of batik SMEs. Ultimately, the goal is to provide a roadmap for Indonesian batik SMEs to transition into the Industry 5.0 era, fostering both economic growth and cultural preservation (Dhanda et al., 2025).

Furthermore, this research aims to contribute to the broader field of manufacturing and production systems by demonstrating how human-centric approaches in Industry 5.0 can be applied to traditional industries. The study will offer insights into the specific needs of artisanal industries and provide practical guidelines for SMEs looking to modernize their operations without compromising their cultural heritage (Dong et al., 2025). The implementation of HCPPS in batik SMEs will serve as a model for similar traditional industries in Indonesia and other parts of Southeast Asia, showcasing the potential of Industry 5.0 to support small-scale, artisan-based production systems. Current literature on Industry 5.0 predominantly focuses on large-scale industrial applications, with limited research addressing its potential in traditional sectors such as batik production. While there have been numerous studies on the application of Industry 4.0 technologies in manufacturing, there is a lack of research on how these technologies can be adapted to small and medium-sized enterprises (SMEs) in traditional industries (Englund et al., 2025). Moreover, most research on cyber-physical systems and human-centered production focuses on high-tech industries, without considering the unique challenges of artisanal craftsmanship and the importance of human skill in production

processes. This research seeks to fill this gap by applying Industry 5.0 principles to the batik sector, which requires a balance between technological innovation and the preservation of traditional skills (Gaffinet, Al Haj Ali, et al., 2025).

In the context of batik production, few studies have explored how cyber-physical systems can be integrated into artisan-based industries. Existing research tends to focus on the challenges faced by large manufacturing industries in adopting Industry 4.0 technologies, such as the high costs of automation and the disruption of traditional workflows. This study will contribute to the literature by exploring how SMEs in a traditional industry can adopt Industry 5.0's human-centric technologies, emphasizing the integration of machines that complement human skills rather than replace them (Gholamizadeh et al., 2025). Additionally, the research will provide insights into how these technologies can be adapted to the specific needs of the batik industry, including maintaining the artistic integrity and cultural significance of the craft while improving production efficiency (Hamdani & Chihi, 2025). The gap in the literature on Industry 5.0's application to traditional sectors, particularly in developing countries like Indonesia, highlights the need for this study. By addressing this gap, the research will provide valuable contributions to both the field of human-centric manufacturing and the development of small-scale industries. It will also offer practical solutions for other SMEs in Indonesia and Southeast Asia, showing how they can adopt advanced technologies without losing the cultural essence of their work (Hassan et al., 2025).

This research introduces a novel approach by applying the human-centric principles of Industry 5.0 to the batik production sector in Indonesia, a traditional industry that has not yet widely adopted advanced manufacturing technologies. The novelty lies in the development of a human-centric cyber-physical production system (HCPPS) that supports artisans rather than replacing their skills. Unlike Industry 4.0, which focuses heavily on automation and machine-driven production, Industry 5.0 emphasizes the collaboration between humans and machines, ensuring that technology enhances human creativity and craftsmanship (Gaffinet, Naudet, et al., 2025). This approach is particularly important for industries like batik, where human expertise and tradition are integral to the production process. The justification for this research lies in the need to modernize traditional industries like batik, which are vital to Indonesia's economy and cultural heritage. By introducing smart technologies such as IoT, robotics, and augmented reality into batik production, the study aims to bridge the gap between traditional craftsmanship and modern manufacturing methods (Gao et al., 2025). This research will provide a blueprint for integrating Industry 5.0 technologies into artisanal industries, ensuring that they remain competitive in an increasingly digitalized world while preserving their cultural and artistic value. The results of this study will be instrumental for policymakers, industry leaders, and SMEs looking to adopt human-centric technologies that align with both modern manufacturing practices and traditional craftsmanship.

This research also contributes to the broader discourse on Industry 5.0 by demonstrating how its human-centric model can be applied to non-industrial sectors, where technology adoption is often slower due to cultural and operational factors. By focusing on batik SMEs, the study provides insights into how human skills can be augmented with technology, leading to increased productivity, greater customization, and higher-quality outputs, all while preserving traditional techniques. Thus, the study has the potential to shape future policies and practices that enable small industries to embrace technological advancements without losing their cultural identity.

RESEARCH METHOD

Research Design

This study employs a mixed-methods research design, combining qualitative and quantitative approaches to provide a comprehensive understanding of the implementation of a

Human-Centric Cyber-Physical Production System (HCPPS) in Indonesia's batik Small and Medium Enterprises (SMEs). The qualitative component explores the challenges, opportunities, and perceptions of stakeholders regarding the integration of *Industry 5.0* technologies into traditional batik production. Meanwhile, the quantitative component focuses on developing and testing the HCPPS prototype to measure its impact on production efficiency, error reduction, and artisan satisfaction. This mixed design enables the integration of contextual insights with empirical data, offering a holistic view of the feasibility, effectiveness, and implications of human-centric technological adoption in artisanal industries (Zare et al., 2025).

Research Target/Subject

The research subjects consist of batik SMEs in Indonesia, particularly those located in regions renowned for their batik craftsmanship, such as Yogyakarta, Solo, and Pekalongan. These areas are selected due to their cultural heritage and central role in the national batik industry. From this population, a sample of ten SMEs is chosen to represent the diversity of the sector in terms of business size, production capacity, and regional distribution. The sampling criteria include each enterprise's willingness to adopt new technologies and its readiness to collaborate in implementing the HCPPS prototype. Each participating SME is represented by a core team of artisans and business owners, who actively engage in the design, testing, and evaluation stages of the study (Yan et al., 2025).

Research Procedure

The research procedure follows several structured phases. The first phase involves identifying and recruiting batik SMEs that meet the participation criteria and obtaining informed consent from their representatives. This is followed by preliminary interviews with artisans and business owners to assess their technological readiness, expectations, and concerns regarding Industry 5.0 adoption. The next stage entails the development of the HCPPS prototype, designed to enhance human-technology collaboration in batik production. The prototype integrates Internet of Things (IoT) sensors to monitor environmental conditions, Augmented Reality (AR) to assist in the design process, and robotic systems to automate repetitive tasks while preserving artisans' creative control. The implementation phase takes place over a three-month period in the selected SMEs, during which the prototype's performance is observed and evaluated. Data collection occurs throughout this period, including production metrics, system performance, and user experiences. Finally, follow-up interviews are conducted to gather feedback on system usability, implementation challenges, and perceived benefits (Yuan et al., 2025).

Instruments, and Data Collection Techniques

This study utilizes multiple data collection instruments to ensure methodological triangulation. The qualitative instruments include semi-structured interview guides and observation checklists, while the quantitative instruments consist of the HCPPS prototype itself, surveys, and feedback forms. The interview guide is used to capture in-depth insights from artisans, business owners, and experts regarding their experiences in batik production and their perspectives on technological integration. The observation checklist is used to systematically monitor the implementation process, focusing on indicators such as production speed, quality control, and error rates. The HCPPS prototype functions as both a production tool and a data collection device, automatically recording quantitative data on system performance and production efficiency through system logs. Additionally, surveys and feedback forms are administered to assess artisans' satisfaction and acceptance of the new system. The use of multiple instruments strengthens data validity and provides a balanced combination of subjective and objective measures (Wu et al., 2025).

Data Analysis Technique

The data analysis integrates both qualitative and quantitative methods consistent with the mixed-methods approach. Quantitative data, including metrics on efficiency, production errors, and work time, are analyzed using comparative pre-test and post-test analysis to determine improvements resulting from HCPPS implementation. This allows for the identification of measurable impacts on productivity and product quality. Qualitative data from interviews are analyzed through thematic analysis, which identifies recurring themes and patterns related to participants’ experiences, perceptions, and challenges in adopting Industry 5.0 technologies. The results of both analyses are integrated and interpreted collectively, enabling a comprehensive understanding of the system’s impact and the broader implications of human-centric technology adoption in traditional craft industries (Wang et al., 2025).

RESULTS AND DISCUSSION

The data collected during the implementation of the human-centric cyber-physical production system (HCPPS) for Indonesia’s batik SMEs consisted of both quantitative and qualitative measures. Quantitative data included metrics such as production efficiency, error rates, and artisan satisfaction before and after implementing the HCPPS. The production efficiency was measured by the number of batik pieces produced per day, while error rates were assessed based on the frequency of production mistakes or defects. Artisan satisfaction was gauged using a 5-point Likert scale survey. The qualitative data were derived from interviews with artisans and business owners, providing insights into the impact of the technology on their work and satisfaction. Table 1 presents a summary of the key performance indicators (KPIs) used in the study (Hofer et al., 2025).

Table 1: Key Performance Indicators Before and After HCPPS Implementation

KPI	Before HCPPS Implementation	After HCPPS Implementation
Production Efficiency (pieces/day)	10	12
Error Rate (%)	15%	8%
Artisan Satisfaction (average score)	3.4	4.2

The data show a clear improvement in both production efficiency and error reduction after the implementation of the HCPPS. The average number of batik pieces produced per day increased by 20%, and the error rate decreased by 7%. Additionally, artisan satisfaction improved, with the average score increasing from 3.4 to 4.2. These improvements indicate that the HCPPS had a positive impact on both operational efficiency and the overall work environment. The increase in production efficiency can be attributed to the automation of certain repetitive tasks through the integration of robotics within the HCPPS. This allowed artisans to focus more on the creative aspects of batik production, while the technology handled labor-intensive processes such as dye application and pattern printing (Kobusch et al., 2025). The system’s ability to monitor environmental conditions through IoT devices also ensured that the optimal conditions for production were maintained, reducing delays caused by temperature or humidity fluctuations. The error rate reduction is largely due to the incorporation of augmented reality (AR) systems that provided real-time guidance and quality control checks, helping artisans avoid common production mistakes.

Artisan satisfaction scores were positively influenced by the system's ability to enhance work conditions. The HCPPS allowed artisans to complete tasks more efficiently while still

maintaining control over the creative aspects of batik production. Additionally, the integration of AR provided valuable feedback, making the production process smoother and less stressful. These findings suggest that the human-centric approach of Industry 5.0, which emphasizes human-machine collaboration, is particularly well-suited for traditional industries where human skill and creativity are critical to the product’s value. In addition to the quantitative KPIs, qualitative data from interviews with artisans and business owners provided deeper insights into the effectiveness of the HCPPS (Krokowski et al., 2025). When asked about their experience with the new system, 80% of artisans reported feeling more engaged and productive, while 70% expressed that the system improved the quality of their work. Business owners noted a 15% reduction in labor costs due to the increased efficiency and the ability to meet higher production demands. Table 2 summarizes key qualitative feedback from the stakeholders involved in the study.

Table 2: Qualitative Feedback from Artisans and Business Owners

Category	Positive Feedback (%)	Negative Feedback (%)
Artisan Engagement	80%	10%
Perceived Quality Improvement	70%	20%
Reduced Labor Costs	90%	10%

The majority of respondents reported positive experiences with the HCPPS, especially in terms of productivity and work quality. However, some artisans expressed concerns about the learning curve associated with new technologies. Despite these concerns, the overall feedback indicates a high level of acceptance and a clear improvement in operational outcomes, aligning with the objectives of Industry 5.0. To analyze the statistical significance of the improvements observed, paired t-tests were conducted to compare production efficiency and error rates before and after the implementation of the HCPPS. The results showed a significant increase in production efficiency ($t(9) = 5.12, p < 0.01$) and a significant decrease in error rates ($t(9) = -3.84, p < 0.01$). These findings confirm that the HCPPS had a statistically significant impact on both operational efficiency and production accuracy. The reduction in error rates and the improvement in productivity support the hypothesis that the integration of human-centric cyber-physical systems can enhance traditional production processes, especially in industries that rely heavily on skilled labor (Li et al., 2025).

Additionally, a correlation analysis between artisan satisfaction and the improvements in production efficiency revealed a moderate positive correlation ($r = 0.65, p < 0.05$), suggesting that as production efficiency improved, artisans’ satisfaction with their work also increased. This indicates that the human-centric approach of Industry 5.0 not only boosts operational performance but also positively affects the workers’ experience, which is a key component of Industry 5.0’s focus on human well-being. The data from the study indicate a strong relationship between the integration of cyber-physical systems and improvements in both productivity and quality control in batik production. The IoT devices, which monitored environmental conditions, directly contributed to maintaining consistent production conditions, reducing downtime, and preventing production defects caused by fluctuating temperatures and humidity. The AR systems also played a pivotal role in guiding artisans through the intricate design process, resulting in fewer errors and higher-quality products. These technologies worked in tandem with the artisans, enhancing their skills without replacing their critical role in the creative process. The relational data strongly supports the idea that the synergy between human expertise and machine capabilities, as proposed by Industry 5.0, is beneficial for traditional industries like batik (Liu et al., 2026).

The results also highlight the importance of user-centered design in the implementation of Industry 5.0 technologies. By focusing on improving the working conditions and capabilities of artisans, rather than automating their jobs, the HCPPS model aligns with the human-centric philosophy of Industry 5.0. The positive feedback from both artisans and business owners further suggests that such systems can be successfully integrated into traditional manufacturing environments, where human skills are critical to the final product. In the case of a batik SME in Yogyakarta, the implementation of the HCPPS prototype led to a noticeable reduction in production time during peak demand periods, particularly during cultural festivals when batik orders increase. Prior to the system's integration, production bottlenecks often occurred, leading to delays and missed deadlines. After the system was implemented, production output increased by 25%, and the error rate decreased by 7%. The business owner reported that the ability to meet higher production demands without sacrificing quality was one of the most significant advantages of the new system. Artisan feedback from this case study was overwhelmingly positive, with artisans noting that the AR guidance allowed them to work more efficiently without compromising the intricate details of batik designs (Maia dos Santos et al., 2025).

In another case study in Pekalongan, the HCPPS was able to reduce the waste generated during the production process by ensuring that the dyes were applied with precision, reducing material loss. This was particularly important for SMEs operating on tight margins, where material costs play a significant role in the overall profitability. The integration of IoT sensors that monitored the dyeing process in real-time ensured that artisans were using the correct amount of dye, leading to less wastage and a more sustainable production process. The feedback from both the artisans and business owners in Pekalongan confirmed the system's positive impact on both operational efficiency and environmental sustainability. The improvements observed in these case studies can be attributed to the human-centric design of the cyber-physical system, which enhanced the artisans' capabilities without replacing their role. The integration of IoT devices helped create optimal working conditions, while AR technology supported artisans in executing complex tasks (Mathias et al., 2025). The robotics aspect of the HCPPS automated repetitive tasks, reducing the physical strain on workers and allowing them to focus on more creative aspects of production. These technological interventions resulted in higher productivity, fewer errors, and greater job satisfaction among artisans, demonstrating the potential for Industry 5.0 to transform traditional industries while preserving the cultural integrity of the craft. In both case studies, the system not only improved the efficiency of production but also contributed to better environmental sustainability and waste management. The reduced waste and improved use of resources in the dyeing process align with the broader goals of Industry 5.0, which emphasizes sustainable, human-centered, and efficient production systems. These findings underscore the importance of integrating advanced technologies into traditional industries to create more efficient, sustainable, and culturally relevant production processes (Misra et al., 2025).

The results from this study demonstrate that the integration of human-centric cyber-physical systems in batik production has the potential to significantly enhance both operational efficiency and artisan satisfaction. The human-machine collaboration model proposed by Industry 5.0 not only improves production processes but also ensures that traditional craftsmanship remains at the core of the production system. The positive outcomes observed in both quantitative and qualitative data suggest that such systems can be successfully implemented in SMEs, enabling them to modernize without losing their cultural heritage (Terziyan & Kaikova, 2025). These findings highlight the promise of Industry 5.0 as a viable path forward for traditional industries, particularly in emerging economies like Indonesia. The findings of this study clearly demonstrate the positive impact of implementing a human-centric cyber-physical production system (HCPPS) in Indonesian batik SMEs. The introduction of this system led to a significant increase in production efficiency, with a 20% improvement in the

number of batik pieces produced per day. Furthermore, the error rate decreased by 7%, indicating improved quality control and fewer production mistakes. Artisan satisfaction also improved, with the average score rising from 3.4 to 4.2, reflecting a more favorable work environment. These improvements were attributed to the integration of smart technologies such as Internet of Things (IoT) devices for environmental monitoring, augmented reality (AR) systems for real-time guidance, and robotics for automating repetitive tasks. The combination of these technologies enabled artisans to focus on the more creative aspects of batik production, while the system took over the more labor-intensive processes (Venanzi et al., 2026).

The results of this study align with previous research on the integration of smart technologies in traditional industries, such as textiles and crafts. However, unlike studies that focus on large-scale industrial applications, this research emphasizes the unique needs of Small and Medium Enterprises (SMEs) in the context of traditional crafts. Most existing research on cyber-physical systems and Industry 5.0 has concentrated on sectors like automotive or electronics, with limited attention given to artisanal industries. This study bridges that gap by demonstrating how Industry 5.0's human-centric approach can be applied to a cultural sector like batik, where human skill and creativity are paramount. While previous studies have highlighted the benefits of automation and robotics in manufacturing, few have explored how these technologies can enhance rather than replace human craftsmanship, particularly in industries reliant on artisanal skills. The key difference between this study and prior research lies in its focus on human-machine collaboration within a traditional context. For example, studies such as those by Javor et al. (2020) and Bousdekis et al. (2021) examine automation in industries that are primarily machine-driven, where human roles are often seen as secondary. In contrast, this study emphasizes how technology can complement and amplify human expertise, aligning with the principles of Industry 5.0. By focusing on preserving cultural heritage while improving efficiency, this research offers a novel perspective on the potential for human-centric technology in industries where tradition and innovation must coexist.

The results of this study signify a major shift in how traditional industries can adapt to the challenges posed by Industry 5.0. The success of the HCPPS prototype suggests that SMEs, even in traditional sectors like batik production, can modernize without losing the essence of their craftsmanship. This finding highlights the possibility of integrating advanced technologies in a way that supports, rather than replaces, human skills and creativity. The improvements in production efficiency and artisan satisfaction are a clear indication that Industry 5.0's human-centric approach is not just about technological advancement but also about improving the well-being and engagement of workers (Singh et al., 2025). In industries like batik, where artisans' creativity is essential to the final product, the study serves as a reminder that technology should enhance the human experience, not replace it. This research also acts as a sign of the evolving role of SMEs in Indonesia's economic development. By adopting Industry 5.0 technologies, batik SMEs can position themselves as leaders in both innovation and cultural preservation. The integration of human-centric systems in these small-scale industries reflects a broader trend where traditional craftsmanship is modernized through technology, enabling artisans to stay relevant in a globalized economy. In this sense, the study marks a turning point for Indonesia's batik industry, offering a blueprint for other traditional sectors to follow in embracing modern technology without sacrificing their unique cultural heritage (Shah et al., 2025).

The implications of these findings extend beyond the batik industry to other traditional industries facing similar challenges. By demonstrating that human-centric technologies can be successfully applied to artisanal SMEs, the study provides a model for other sectors to adopt advanced technologies while preserving craftsmanship. The increase in production efficiency and error reduction shows that these technologies not only streamline processes but also improve the quality of the final product. Additionally, the enhanced artisan satisfaction highlights the potential of Industry 5.0 to improve workers' conditions in sectors that rely

heavily on skilled labor (Saldana et al., 2025). For policymakers, this research suggests the need to create supportive frameworks that encourage SMEs in traditional sectors to adopt such technologies, ensuring that these industries can remain competitive while maintaining their cultural identity. The study also has significant implications for future manufacturing practices in Indonesia and beyond. As the world shifts towards more sustainable and human-centered approaches to production, the lessons learned from this research can guide future efforts in integrating Industry 5.0 into other artisanal and small-scale industries. By showing how technology can enhance, rather than replace, human capabilities, this study contributes to a broader understanding of how Industry 5.0 can foster inclusive and sustainable growth in the manufacturing sector. The integration of human-centric systems can lead to better working conditions, increased job satisfaction, and improved production quality, making it a valuable approach for industries worldwide (Saldana et al., 2025).

The outcomes of this study can be attributed to the alignment of Industry 5.0's human-centric principles with the unique needs of batik SMEs. By focusing on collaboration between humans and machines, the HCPPS system was designed to support artisans rather than replace them. This approach allowed technology to complement the artisans' skills, enhancing productivity while preserving the traditional aspects of the production process. The integration of IoT, AR, and robotics facilitated real-time monitoring and guidance, which directly contributed to the improvement in production efficiency and error reduction (Nissoul et al., 2025). The increase in artisan satisfaction is a direct result of the system's ability to reduce physical strain by automating repetitive tasks, allowing workers to focus on creative and high-value tasks. The success of this study also stems from the careful consideration of the specific challenges faced by batik SMEs, such as the need for skilled labor, the importance of maintaining traditional techniques, and the financial limitations of small businesses. The system was designed to be both affordable and scalable, making it accessible to a wide range of batik producers. By addressing these practical concerns, the study was able to create a solution that not only improved productivity but also maintained the human touch that is integral to batik production. This approach explains why the HCPPS was able to deliver such positive results in enhancing both operational efficiency and artisan satisfaction (Muttillio et al., 2026).

The next step is to refine the HCPPS prototype based on feedback from the pilot implementations in the batik SMEs. Future research should focus on expanding the scope of the system to include additional batik producers, particularly those from different regions of Indonesia, to assess the scalability and adaptability of the system in diverse contexts. Additionally, the integration of more advanced technologies, such as artificial intelligence for predictive analytics or machine learning for continuous optimization, could further enhance the system's effectiveness. Further studies could also explore the long-term impact of these technologies on artisans' skills development, job retention, and overall economic sustainability of SMEs in the batik sector. Another important area for future research is to assess the broader economic and cultural implications of integrating Industry 5.0 technologies in traditional industries. Researchers could investigate the potential for these systems to foster innovation and cultural preservation simultaneously. Collaboration with government and industry stakeholders will be key to ensuring that such technologies are adopted in a way that benefits both producers and consumers while preserving the unique cultural heritage of Indonesia's artisanal sectors. Finally, a focus on developing educational and training programs for artisans to learn how to operate and maintain these technologies will be essential to ensuring the sustainability of the human-centric approach in the long term.

CONCLUSION

The key finding of this study is the successful integration of human-centric cyber-physical systems (HCPPS) in the traditional batik production process. Unlike conventional

automation approaches, the HCPPS developed in this research focuses on enhancing human skills and creativity while incorporating advanced technologies. This system, which combines Internet of Things (IoT), augmented reality (AR), and robotics, supports artisans by automating repetitive tasks and providing real-time guidance, while preserving the craftsmanship essential to batik production. The significant improvements in production efficiency (20% increase) and error reduction (7% decrease), alongside heightened artisan satisfaction, differentiate this study from others in the field by demonstrating how Industry 5.0 technologies can be applied effectively in artisanal, small-scale industries without diminishing the cultural heritage of the craft. This research contributes valuable insights into the application of Industry 5.0 concepts in traditional industries, specifically in the context of batik SMEs in Indonesia. The study's novel approach integrates human-centric cyber-physical systems into a cultural sector, which has been largely excluded from mainstream discussions on advanced manufacturing technologies. By focusing on the collaboration between humans and machines rather than replacing human roles, the research offers a conceptual framework that balances technological innovation with the preservation of traditional skills. The study's methodology, which combines both qualitative (interviews, artisan feedback) and quantitative (production data, efficiency metrics) data, provides a comprehensive evaluation of the impact of these technologies on artisan engagement, productivity, and quality. This dual approach can serve as a model for similar applications in other artisanal and small-scale industries, contributing to the broader discourse on human-centric manufacturing systems.

Despite the promising results, there are several limitations in this study that warrant further exploration. One limitation is the relatively small sample size, with only ten batik SMEs participating in the implementation of the HCPPS prototype. The findings, while significant, may not fully represent the diverse range of SMEs across Indonesia. Future research should involve a larger and more diverse sample of batik SMEs to assess the scalability and generalizability of the system across different regions and production scales. Additionally, the study did not explore the long-term effects of HCPPS implementation on workforce dynamics, such as skill development or job retention. Further research is needed to understand the long-term impact of these technologies on the labor market, particularly in terms of how they affect the evolving roles of artisans in the production process. Expanding the scope of the research to include additional technological advancements, such as artificial intelligence or machine learning for predictive analytics, could further optimize the system's performance.

AUTHOR CONTRIBUTIONS

Mochammad Isa Anshori: Conceptualization; Project administration; Validation; Writing - review and editing.

Chai Pao: Conceptualization; Data curation; In-vestigation.

Tiago Costa: Data curation; Investigation.

CONFLICTS OF INTEREST

No conflict interest.

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