



## Development and Evaluation of an IoT-Based Smart Manufacturing Framework for SMEs

Amenda Septiala Tarigan<sup>1,\*</sup>, Ayu Nova Rahmawati<sup>2</sup>, Andicho Haryus Wirasapta<sup>3</sup>

<sup>1</sup> Industrial Engineering Department, Universitas Pembangunan Nasional Veteran Jakarta, Depok, Indonesia

<sup>2</sup> Industrial Engineering Department, Universitas Pasundan, Bandung, Indonesia

<sup>3</sup> Electrical Engineering and Informatics Department, Universitas Jambi, Jambi, Indonesia

\*Corresponding author email: [amenda.tarigan@upnvj.ac.id](mailto:amenda.tarigan@upnvj.ac.id)

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### ABSTRACT

Small and Medium Enterprises (SMEs) play an important role in economic growth; however, many SMEs still face challenges related to productivity, operational efficiency, and technological adoption. The development of Internet of Things (IoT) technologies provides opportunities for SMEs to improve operational visibility and automation toward smart manufacturing systems. This study aims to develop a simplified IoT-based smart manufacturing framework for SMEs and validate the framework through laboratory-scale implementation. The research employed a qualitative and experimental approach consisting of literature analysis, framework development, laboratory-scale implementation, and system evaluation. The literature analysis identified that most IoT implementations in SMEs focus on real-time monitoring and basic automatic control using low-cost technologies such as sensors, microcontrollers, and wireless communication platforms. Based on these findings, a five-layer framework consisting of the Data Acquisition Layer, Monitoring Layer, Control Layer, Integration Layer, and Smart Decision Layer was proposed. To validate the framework, a laboratory-scale IoT monitoring and control system was developed using NodeMCU ESP8266, DHT11 sensor, MQ-series gas sensor, ultrasonic sensor, relay module, and IoT dashboard platform. The developed system successfully demonstrated real-time monitoring and automatic control capabilities under laboratory conditions. The results indicate that affordable IoT technologies are feasible for supporting the

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gradual adoption of smart manufacturing systems in SMEs. The proposed framework provides practical guidance for SMEs to progressively adopt IoT technologies according to their operational capabilities, with future integration of AI/ML-based decision support envisioned to enhance predictive and autonomous functionalities.

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## 1. Introduction

Small and Medium Enterprises (SMEs) play a crucial role in supporting economic growth, particularly in developing countries such as Indonesia [1], [2]. SMEs contribute significantly to employment, local production, and economic resilience. However, many SMEs still face challenges related to productivity, process consistency, and operational efficiency due to limited resources, lack of technological adoption, and insufficient operational optimization [3], [4]. These challenges are often caused by the reliance on manual processes and limited adoption of modern technologies, which restrict SMEs' productivity and reduce their competitiveness in an increasingly digital and globalized market [5], [6].

In recent years, the development of the Internet of Things (IoT) has emerged as a promising solution to enhance operational performance in SMEs. IoT enables the integration of sensors, devices, and communication technologies to collect and transmit real-time data from production environments [7]. As a key enabling technology of Industry 4.0, IoT facilitates connectivity between physical assets and digital systems, allowing organizations to improve operational visibility, responsiveness, and resource utilization. Through IoT-based systems, SMEs can monitor production processes, environmental conditions, and inventory levels more effectively. This capability supports data-driven decision-making and improves transparency in operational activities, which are essential elements in the transition toward smart manufacturing [8], [9]. Furthermore, IoT adoption has been reported to positively influence organizational performance and supply chain effectiveness by enabling real-time information sharing and process integration [10], [11].

Several studies have demonstrated the implementation of IoT in SMEs across various domains, including production monitoring, environmental control, and inventory management. These implementations commonly utilize low-cost sensors and microcontrollers to capture data such as pH levels, gas concentration, and stock conditions [12], [13], [14]. The collected data enable real-time monitoring and improve process visibility, allowing SMEs to better control their operational activities. In some cases, IoT systems are also integrated with basic control mechanisms, enabling automatic responses such as activating ventilation systems or regulating environmental conditions based on sensor readings [14]. Recent studies have also emphasized that affordable and scalable IoT technologies can

serve as an effective entry point for SMEs to begin their digital transformation journey toward Industry 4.0 environments [15], [16], [17].

Despite these advancements, the current implementation of IoT in SMEs remains limited in scope. Most existing systems are primarily focused on monitoring functions rather than comprehensive system integration or intelligent decision-making. The lack of integration between production, inventory, and environmental systems results in fragmented automation. Furthermore, advanced capabilities such as predictive analytics and autonomous control are rarely implemented due to cost constraints and limited technical expertise within SMEs [18]. This indicates that IoT adoption in SMEs is still at an early stage and has not fully achieved the characteristics of smart manufacturing systems. Several studies have reported that SMEs continue to face technological, organizational, and financial barriers when implementing advanced Industry 4.0 technologies, resulting in slow progression from isolated digital solutions toward fully integrated smart manufacturing systems [16], [19], [20], [21].

Therefore, there is a need for a structured approach that not only explains the current implementation of IoT in SMEs but also provides a practical pathway toward smart manufacturing adoption. A framework is required to guide SMEs in implementing IoT technologies in a progressive and integrated manner. Although previous studies have proposed various Industry 4.0 and smart manufacturing adoption models, many are designed for large enterprises or require substantial technological investment, making them difficult to apply in resource-constrained SMEs [15], [17], [20].

Unlike previous studies that mainly focus on isolated IoT monitoring applications in SMEs, this study proposes an integrated five-layer framework that illustrates the gradual transition from basic IoT monitoring systems toward smart manufacturing adoption. In addition, the proposed framework is evaluated through laboratory-scale implementation to demonstrate its practical feasibility and applicability for SMEs with limited technological resources.

This study aims to develop a simplified IoT-based framework for smart manufacturing adoption in SMEs and to validate the proposed framework through a laboratory-scale implementation. The framework is constructed based on observed implementation patterns and is evaluated by applying it in a controlled environment to demonstrate its feasibility and practical applicability. The results are expected to provide both conceptual and practical contributions to the adoption of IoT in SME manufacturing systems.

## **2. Methods**

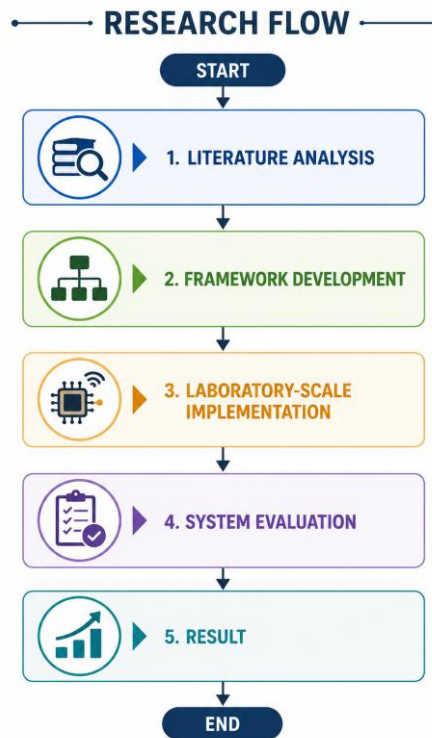
This study employed a qualitative and experimental approach to develop and validate a simplified IoT-based framework for smart manufacturing adoption in Small and Medium Enterprises (SMEs). The

methodology combined literature-based analysis with laboratory-scale implementation in order to provide both conceptual and practical validation of the proposed framework. The research process consisted of literature analysis, framework development, laboratory-scale implementation, and system evaluation.

This study was not designed as a systematic literature review using protocols such as PRISMA or Kitchenham. Instead, the literature analysis was conducted to support framework development by identifying common implementation patterns, technological characteristics, and research gaps related to IoT adoption and smart manufacturing in SMEs. This approach is consistent with framework development studies, where literature findings are synthesized to establish conceptual foundations and design principles rather than to perform exhaustive evidence aggregation [15], [17], [20].

The first stage involved conducting a literature analysis on the implementation of Internet of Things (IoT) technologies in SMEs. Several previous studies related to production monitoring, environmental control, inventory management systems, Industry 4.0 adoption, and smart manufacturing frameworks were reviewed to identify current implementation trends and technological characteristics [5], [6], [7]. The selected literature was chosen based on its relevance to IoT applications in SMEs, smart manufacturing adoption, Industry 4.0 implementation, and framework development. Priority was given to recent and representative studies that addressed technological implementation, adoption challenges, integration approaches, and operational impacts in SME environments [19], [20], [21], [22]. The analysis focused on identifying commonly used hardware components, including sensors, microcontrollers, communication modules, and IoT platforms. In addition, the operational benefits and limitations of existing systems were also examined. Previous studies showed that most IoT implementations in SMEs emphasize monitoring capabilities using low-cost and scalable technologies, while intelligent decision-making and system integration remain limited [3], [4].

Based on the literature findings, a simplified IoT-based smart manufacturing framework for SMEs was developed. The framework was designed to represent the gradual adoption process of IoT technologies in SMEs, starting from data acquisition and monitoring functions toward more advanced control and system integration capabilities. The proposed framework consists of five layers, namely the data acquisition layer, monitoring layer, control layer, integration layer, and smart decision layer. The overall research flow for the development and laboratory-scale validation of the proposed IoT-based smart manufacturing framework for SMEs used in this study is illustrated in Fig. 1.



**Figure 1:** Flowchart of Research Development.

The framework structure was derived from recurring concepts identified in the reviewed literature, including IoT-enabled monitoring, cyber-physical connectivity, system integration, and intelligent operational support within Industry 4.0 environments [10], [11], [23]. The layered structure was intended to provide a practical pathway for SMEs in implementing IoT technologies progressively according to their technological readiness and operational requirements.

To validate the proposed framework, a laboratory-scale IoT monitoring and control system was developed using affordable hardware components that are commonly adopted in SMEs. The implementation utilized a NodeMCU ESP8266 microcontroller, DHT11 temperature and humidity sensor, MQ-series gas sensor, ultrasonic sensor, relay module, and an exhaust fan as an actuator simulation. The sensors were used to collect environmental and operational data in real time, while the NodeMCU module transmitted the collected data wirelessly to an IoT dashboard platform for monitoring purposes.

The developed system demonstrated the interaction between sensing, monitoring, and automatic control functions within the proposed framework. Environmental parameters such as temperature, humidity, gas concentration, and object distance were continuously monitored and visualized through the dashboard system. Furthermore, the relay module enabled automatic control by activating the exhaust fan whenever the measured gas concentration exceeded a predefined threshold value. This mechanism was intended to simulate a basic smart manufacturing environment where monitoring systems are integrated with automatic operational responses.

The system evaluation stage focused on assessing the functionality and feasibility of the developed IoT system for SME applications. The evaluation considered several aspects, including real-time data acquisition performance, sensor responsiveness, communication reliability, monitoring capability, and automatic control performance. The evaluation results were then analyzed to determine the practicality of the proposed framework in supporting the gradual transition of SMEs toward smart manufacturing systems.

### **3. Results and Discussion**

#### **3.1. Analysis of IoT Implementation in SMEs**

The literature analysis showed that Internet of Things (IoT) technologies have been increasingly implemented in SMEs across several operational domains, particularly in production monitoring, environmental control, and inventory management systems. Most implementations utilized low-cost hardware components such as NodeMCU ESP8266, Arduino-based microcontrollers, temperature and humidity sensors, gas sensors, ultrasonic sensors, and wireless communication modules[12], [13], [14]. The adoption of affordable devices indicates that SMEs tend to prioritize practical and scalable solutions that can be implemented with minimal investment and technical complexity.

The reviewed studies also demonstrated that IoT technologies enable SMEs to improve operational visibility through real-time monitoring systems. In the hydroponic monitoring system developed by Ma'rifatillah *et al.*[12], IoT sensors were used to continuously monitor environmental parameters related to cultivation conditions. Similarly, Batara and Yosephine[13] implemented an IoT-based inventory monitoring system using ultrasonic and infrared sensors to improve stock management accuracy and operational transparency. In addition, Putri *et al.* [14] integrated IoT technology with a fuzzy logic control mechanism to automatically regulate kitchen smoke conditions in SME food production environments.

Despite these advantages, the analysis revealed that most existing IoT implementations in SMEs remain focused on isolated monitoring and basic control functions. The systems are generally designed to solve specific operational problems rather than supporting fully integrated smart manufacturing environments. Most studies emphasize monitoring capability, while only a limited number implement automatic control responses or system integration between production, environmental, and inventory functions[8], [9]. This condition indicates that IoT adoption in SMEs is still at an early stage and has not yet achieved comprehensive smart manufacturing characteristics such as intelligent decision-making, predictive analytics, and integrated operational management [18]. This finding is consistent with studies showing that many SMEs remain in the early stages of Industry 4.0 adoption, where digital initiatives are

often implemented as stand-alone solutions rather than integrated smart manufacturing systems[15], [16], [17], [19], [21].

Another important finding is that current IoT adoption in SMEs is strongly influenced by cost efficiency and ease of implementation. Most SMEs prefer low-cost and modular technologies due to financial limitations and limited technical expertise [5], [6]. As a result, the implementation of advanced technologies such as artificial intelligence, machine learning, and autonomous decision systems remains relatively uncommon. This creates a technological gap between basic IoT monitoring systems and fully integrated smart manufacturing systems.

### 3.2. Proposed IoT-Based Smart Manufacturing Framework

A simplified IoT-based smart manufacturing framework for SMEs was proposed. The framework as illustrated in Fig. 2 was designed to represent the gradual transition process of SMEs from basic monitoring systems toward integrated smart manufacturing environments.

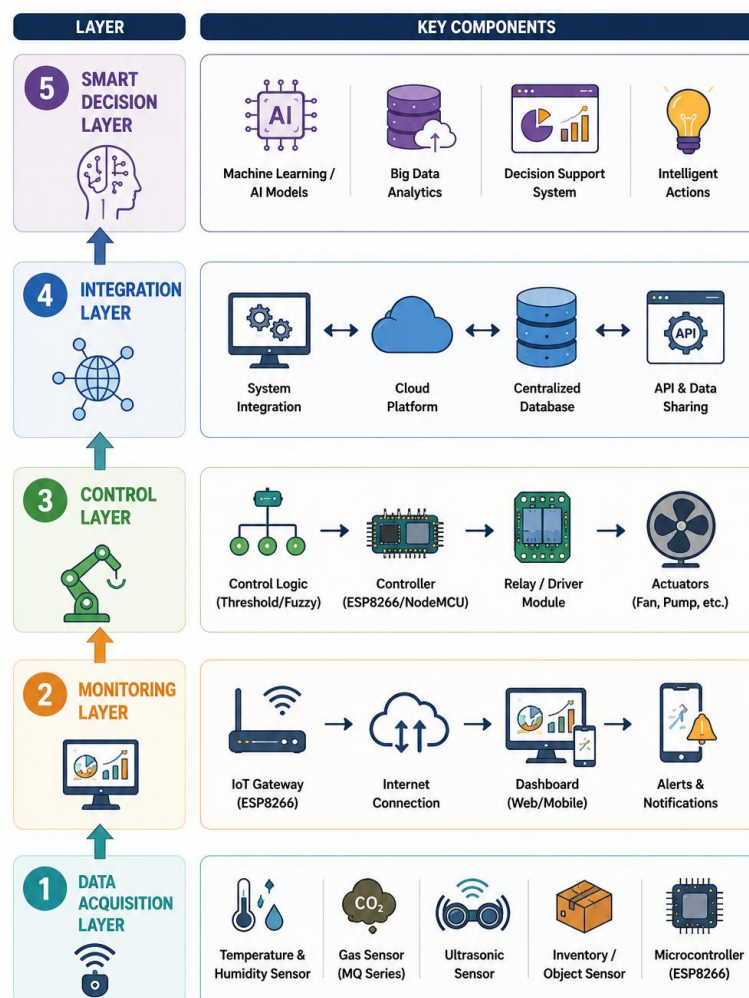


Figure 2: Proposed IoT-based smart manufacturing framework for SMEs.

The framework emphasizes progressive technology adoption using affordable and scalable IoT solutions suitable for SMEs with limited operational resources. This framework consists of five interconnected layers: Data Acquisition, Monitoring, Control, Integration, and Smart Decision. The layered structure illustrates the evolution of IoT adoption in SMEs, with each layer representing a higher level of technological capability and operational intelligence. It was inspired by key Industry 4.0 and smart manufacturing concepts, including cyber-physical connectivity, data integration, intelligent decision support, and progressive technology adoption in SMEs [11], [15], [17], [23].

The first layer, namely the Data Acquisition Layer, functions as the foundation of the framework. This layer involves the use of sensors and IoT devices to collect operational and environmental data from production systems. Common devices identified in the reviewed studies include temperature sensors, humidity sensors, gas sensors, ultrasonic sensors, and microcontrollers such as NodeMCU and Arduino [12], [13], [14].

The second layer is the Monitoring Layer, where the collected data are transmitted and visualized through IoT platforms or dashboards. This layer enables SMEs to monitor production conditions, inventory status, and environmental parameters in real time. Most current IoT implementations in SMEs are concentrated at this level because monitoring systems are relatively affordable and easy to implement [7], [8].

The third layer is the Control Layer, which introduces automatic response mechanisms into the system. In this layer, IoT systems are integrated with actuators or relay modules to enable automatic operational responses based on sensor readings. For example, exhaust fans or cooling systems can be activated automatically when environmental conditions exceed predefined thresholds[14].

The fourth layer is the Integration Layer, which represents the connection between multiple operational systems such as production monitoring, inventory management, and environmental control. This layer supports data sharing and operational coordination between different functions within SMEs[8], [9]. However, based on the literature findings, this layer is still rarely implemented due to technical and financial limitations.

The final layer, called the Smart Decision Layer, represents a potential future stage for IoT adoption in SMEs [7], [18]. The objective of this layer is to enable autonomous operational optimization and data-driven strategic decision-making. In this stage, advanced technologies such as predictive analytics and machine learning could be incorporated to enable intelligent decision support, but these capabilities are not implemented in the current laboratory-scale validation.

The proposed framework demonstrates that smart manufacturing adoption in SMEs should be viewed as a gradual and scalable process rather than an immediate technological transformation. By adopting IoT technologies incrementally, SMEs can improve operational visibility and automation capabilities while minimizing implementation risks and financial burdens.

### **3.3. Research Contribution**

This study contributes to the existing literature by proposing a simplified and scalable IoT-based smart manufacturing framework specifically designed for SMEs. Unlike existing Industry 4.0 adoption models that are often intended for larger organizations or require substantial technological investment [15], [17], [20], the proposed framework emphasizes affordability, scalability, and gradual implementation. The framework integrates sensing, monitoring, control, system integration, and intelligent decision-support concepts within a single layered structure.

From a theoretical perspective, this study provides a structured conceptual pathway that connects basic IoT implementation with the gradual development of smart manufacturing capabilities in SMEs. The framework extends previous IoT implementation studies by illustrating the relationship between monitoring systems, control mechanisms, integration functions, and intelligent operational decision-making within SME environments.

From a practical perspective, the proposed framework offers guidance for SMEs in adopting IoT technologies using affordable and scalable components. The laboratory-scale implementation further demonstrates the feasibility of integrating low-cost sensors, microcontrollers, wireless communication systems, and automatic control mechanisms into a simplified smart manufacturing environment. Therefore, the framework can serve as a reference for SMEs seeking to gradually transition toward smart manufacturing systems with limited technological and financial resources.

### **3.4. Laboratory-Scale Implementation**

To validate the proposed framework, a laboratory-scale IoT monitoring and control system was developed using low-cost hardware components. The implementation utilized a NodeMCU ESP8266 microcontroller connected with a DHT11 temperature and humidity sensor, MQ-series gas sensor, ultrasonic sensor, relay module, and an exhaust fan actuator. The developed system represented the implementation of the first three layers of the proposed framework, namely data acquisition, monitoring, and control.

The sensors continuously collected environmental and operational data in real time. The acquired data were transmitted wirelessly to an IoT dashboard platform, allowing monitoring activities to be

performed remotely. In addition, the system implemented an automatic control mechanism in which the relay module activated the exhaust fan whenever gas concentration exceeded a predefined threshold value. The implementation approach was adapted from several previous IoT monitoring and automatic control studies in SMEs [12], [13], [14].

The laboratory-scale implementation demonstrated that low-cost IoT technologies can support basic smart manufacturing functionalities in SMEs. The developed system successfully integrated sensing, monitoring, communication, and automatic control capabilities within a simple operational environment. This implementation also confirmed the practicality of the proposed framework for gradual adoption in SMEs with limited technological readiness and financial resources.

### **3.5. System Evaluation and Discussion**

The developed system was evaluated based on monitoring capability, communication reliability, and automatic response performance. The results showed that the system was capable of transmitting sensor data in real time with stable communication performance under laboratory conditions. The monitoring dashboard successfully displayed operational data continuously, enabling improved visibility of environmental conditions.

The automatic control mechanism also functioned properly during the testing process. The relay module responded automatically when predefined threshold conditions were exceeded, demonstrating the feasibility of integrating basic control functions into IoT-based SME systems. This capability supports the transition from passive monitoring systems toward more responsive operational environments.

Although the developed system demonstrated promising results, several limitations were identified. The implementation was conducted only at laboratory scale and did not involve direct deployment in industrial SME environments. Additionally, the current system does not include advanced functionalities like predictive analytics, cloud-based optimization, or intelligent decision-making [7], [18]. These could be considered in future work to further enhance the framework toward fully integrated smart manufacturing systems.

Overall, the findings indicate that IoT technologies can improve SME operational efficiency through real-time monitoring and automatic control. The findings also support studies suggesting that gradual technology adoption is more feasible for SMEs than full-scale smart manufacturing transformation [16], [20], [21]. However, achieving smart manufacturing still requires system integration, technological readiness, and intelligent operational capabilities.

## 4. Conclusion

This study proposed a simplified IoT-based smart manufacturing framework for SMEs through literature analysis and laboratory-scale validation. The findings showed that current IoT implementation in SMEs is mainly focused on monitoring and basic control systems using low-cost technologies such as sensors, microcontrollers, and wireless communication platforms. However, system integration and intelligent decision-making capabilities are still limited.

Based on the identified implementation patterns, a five-layer framework consisting of the Data Acquisition Layer, Monitoring Layer, Control Layer, Integration Layer, and Smart Decision Layer was developed. The framework provides a structured pathway for the gradual adoption of IoT technologies toward smart manufacturing in SMEs. The laboratory-scale implementation demonstrated that affordable IoT technologies are capable of supporting real-time monitoring and automatic control functions, indicating the feasibility of the proposed framework for gradual smart manufacturing adoption in SMEs.

This study was limited to laboratory-scale implementation and did not involve direct industrial deployment. Future studies are recommended to validate the framework in actual SME environments. In addition, the integration of predictive analytics, machine learning, and AI-based decision-support systems may further enhance the framework and support the development of more intelligent smart manufacturing systems for SMEs.

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