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Article

Open-source Software for Developing Appropriate Smart Manufacturing Technology for Small and Medium-sized Enterprises (SMEs)

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Manufacturing innovation promoted by the Fourth Industrial Revolution presents various technologies and policies for implementing future smart factories based on advances in information and communication technology (ICT). However, despite recent advances in smart manufacturing technologies, several difficulties in migrating conventional manufacturing to smart factories remain, particularly in small and medium-sized enterprises (SMEs). Among the recently emerging technologies, ICT-related technologies have been developed and utilized as open-source software (OSS) to accelerate their development through collective intelligence and community growth. In this study, to facilitate the identification of appropriate smart manufacturing solutions for personnel in SMEs with insufficient prior experience and knowledge using OSS, several reference architectures (RAs) are investigated to define a small RA that can be referenced to configure the mandatory functions during development as technical requirements. Subsequently, user-oriented requirements are summarized to determine the enabling OSS by considering the conditions of SMEs for the functional components in developing appropriate smart manufacturing technologies to form Internet of Things edge computing, and a recommendation for enabling OSS that guides the development of SMEs is proposed. In the evaluation, a small edge and gateway demonstration is performed using two single-board computers equipped with Raspberry Pi, where some of the recommended enabling OSS of Message Queuing Telemetry Transport via Wi-Fi, MySQL, Node-RED, and Python are used. Finally, the feasibility of the proposed approach is confirmed by evaluating the demonstration.

KEYWORDS: Appropriate manufacturing technology, Open-source software, Smart factory, Small and medium-sized enterprises, Internet of things, Edge computing

Introduction

Manufacturing innovation promoted by the Fourth Industrial Revolution presents various technologies and policies for implementing future smart factories based on advances in Information and Communication Technology (ICT). Smart manufacturing encompasses various connections among enterprises, industries, demand and supply, and process and value chains within enterprises, and pursues new business models through cross-border convergence. Therefore, smart manufacturing technology requires the horizontal integration of production systems, product lifecycles, and manufacturing businesses with the digitalization of operation data, virtual simulation in digital space, and real-time information sharing. In addition, a vertically integrated infrastructure that connects digitalized components from the production site to the managers for decision-making is necessitated. As shown in Figure 1, recently emerging ICTs such as the Internet of Things (IoT), smart sensors, edge computing, and deep learning are vital to the digital transformation of the manufacturing industry (Kim, Jung *et al*., 2022).

Despite the advantages and advances of smart manufacturing technologies, several difficulties remain in migrating conventional manufacturing to smart factories. First, software- or control-related expertise is necessary to select and use emerging ICTs, which increases the total cost of ownership

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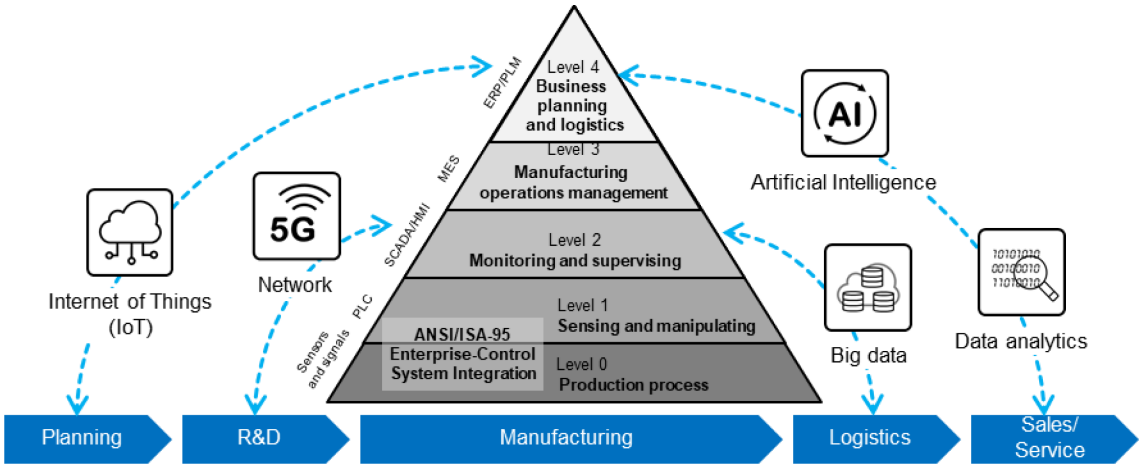

Figure 1. Emerging ICTs in manufacturing digitalization.

(TCO) because most of these technologies are still in the development phase of the technology life cycle. In addition, most manufacturing firms are not prepared for the recent changes, particularly software development. Therefore, the effectiveness and applicability of smart manufacturing technologies vary depending on a company's size and capability (Kim *et al.*, 2019; OECD, 2021). In general, difficulties arise when these emerging technologies are used in manufacturing sites by personnel without ICT experience. In general, large companies with sufficient investment capacity and research capabilities can afford a virtuous cycle of high productivity and added value using smart manufacturing technologies. However, small and medium-sized enterprises (SMEs) have not been able to actively accept these new technologies in recent years because of their limited internal capabilities, such as their investment conditions and development environments (Kim, Lee *et al.*, 2022). Hence, an appropriate approach that focuses on the challenges in digital transformation encountered by SMEs must be developed (Jung *et al.*, 2021; Kim *et al.*, 2019). SMEs account for most businesses in major manufacturing countries and produce low-value-adding components in the production value chain (Arendt, 2008). Consequently, further investigations into cost-effective and user-friendly smart manufacturing technologies can promote bottom-up innovation for SMEs and the manufacturing ecosystem.

Among the recently emerging technologies, ICT-related technologies have been developed and utilized as open-source software (OSS) to accelerate their development through collective intelligence and community growth. In modern software development, OSS reduces development and deployment costs while enabling high-quality products to be operated inexpensively and without restrictions of intellectual property rights (Kim *et al.*, 2019). Therefore, if mandatory OSS for developing smart manufacturing technology for SMEs is systematically organized and provided adequately, then the abovementioned approach can be an excellent digital transformation option for manufacturing SMEs that cannot readily adopt expensive commercial technologies. In this study, software reference architectures (RAs) are investigated and a literature review is performed to develop appropriate smart manufacturing technologies for SMEs or developing countries. A small RA is proposed, and enabling OSS that can be used to develop appropriate smart manufacturing techniques for SMEs are recommended. Finally, the feasibility of the proposed approach is evaluated via demonstration.

Literature Review

1. Brief history and characteristics of OSS

During the development of computers between the 1950s and 1960s, most software was developed in open collaboration and considered a bundle of hardware. However, as computers became popular in the late 1970s, the era of commercial software began, which enabled computer vendors and software companies to purchase and use their software for individual products. In the mid-1980s, major activities such as the GNU (GNU is not a Unix) project in 1983, the Free

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Software Foundation in 1985, and the GNU General Public License (GPL) distribution in 1989 were developed as alternatives to free software to manage the increase in closed licensing and software usage costs. Linux, the largest community-developed and most widely used operating system, was developed and distributed in the form of GPL in 1991. Henceforth, in the early 2000s, web-based information technology companies have achieved significant success using OSS, thus promoting the emergence and utilization of various OSS.

Currently, OSS is a collective term for codes that copyright holders can access, modify, and redistribute unrestrictedly by disclosing the source code; its concept is different from that of commercial or proprietary software. For a detailed definition of OSS, readers can refer to the definitions of open-source initiatives (Open Source Initiative, 2007). Based on those definitions, OSS is regarded as more valuable than commercial software in terms of the following features (Red Hat, 2019):

- Flexibility: The OSS emphasizes modification. This feature enables the developer to customize codes for certain problems without having to use the code in any specific manner.
- Reliability and transparency: Most OSS communities are active, and their codes can be fixed and enhanced by various supporters, unlike proprietary software maintained by a single developer or company. In addition, OSS allows developers to verify and monitor the codes without relying on vendors.
- Free of charge: Although OSS incurs a TCO, open-source licensed software is typically offered free of charge. As such, using OSS can reduce the development cost.
- Stability: A professional developer collaboration network maintains the most widely used OSS.

Based on the 2022 "Open Source Security and Risk Analysis" report, in an analysis of more than 2,400 commercial codebases across 17 industries, 97% of the projects involved the use of OSS, and 78% of the codebases were OSS (Synopsys, 2022). In addition, that the number of users of GitHub, an open-source development community service, has increased by 35% annually indicates that the use of open sources has increased significantly (GitHub, 2021). This implies that OSS not only offers economic benefits, but also increases the social value of sustainable development by presenting another method of software development and utilization based on unique mechanisms that can be participated, improved, and used by all.

2. OSS for the manufacturing sector

Recently, data and connectivity are emphasized in the Intelligence and digitalization of the manufacturing industry, which is represented by smart factories. In addition, the reduced price of computing components and the development of ICTs enable the rapid acquisition, analysis, and deployment of operational data through digital transformation. However, despite the advantages and possibilities of recent ICT developments, the discrepancy in technology adoption between large and small enterprises continues to widen. Moreover, because this digital transformation is vital to sustainable development through increasing productivity and reducing energy, the abovementioned discrepancy further accelerates inequality (OECD, 2021; Prause, 2019).

In terms of software, commercial technologies for achieving intelligence and digitization are expensive to manufacturing SMEs; the costs incurred by such technologies include their prices, the TCO, and operating costs (including licensing). Meanwhile, the recent ICT development in OSS will allow smart manufacturing technology, which is important for data and connection, to be developed more easily and affordably.

Researchers have suggested two valuable concepts for SMEs and the current ICT development trend: Smart retrofitting (Guerreiro *et al*., 2018) and appropriate smart factories (Jung *et al*., 2021). First, the aim of smart retrofitting is to apply Industry 4.0 technology to manufacturing equipment and processes with minimal cost and time. Modifications to conventional manufacturing equipment, such as machine tools, industrial robots, and process plants, have been reported continuously, and studies pertaining to them have confirmed the usefulness of OSS for development (Di Carlo *et al*., 2021; García *et al*., 2020; Sezer *et al*., 2018). Second, an appropriate smart factory has been proposed for applying smart manufacturing technologies with user-friendly and affordable functions to SMEs. This concept can be effectively used for on-site utilization when a generalized commercial system cannot be applied readily to various field configurations of SMEs. Furthermore, this on-site utilization can be implemented using open-source or royalty-free

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resources, which can reduce the development burden.

In addition to these new approaches, OSS-based smart manufacturing technologies using IoT, vision, and deep learning have been continuously proposed (Kim *et al.*, 2019; Kwon *et al.*, 2021). However, even in the current favorable environment, OSS technologies must be identified accurately and used for the digital transformation of SMEs.

Enabling OSS for Appropriate Smart Manufacturing

Despite the advantages and recent trends of OSS usage, SMEs without an ICT workforce encounter difficulties in identifying and evaluating various OSS, unlike academies, research institutes, and large companies (Moeuf *et al.*, 2020). Therefore, to facilitate the identification of appropriate smart manufacturing solutions for SME personnel with insufficient prior experience and knowledge, several RAs are investigated in this study to identify a small RA that can be referenced to configure mandatory functions during development as technical requirements. Subsequently, user-oriented requirements are summarized to determine the enabling OSS by considering the conditions of SMEs for functional components in developing appropriate smart manufacturing technologies to form IoT edge computing. Finally, a recommendation for enabling OSS to guide the development of SMEs is proposed and evaluated. Figure 2 shows the overall approach for determining the enabling OSS from the technical side to the field side (i.e., SMEs).

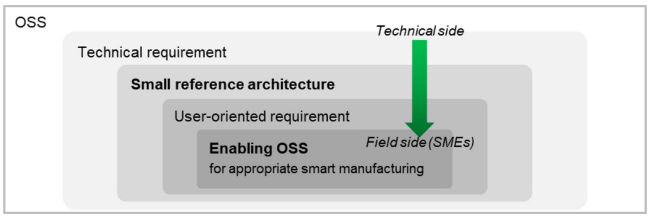


Figure 2. Overall approach of narrowing down enabling OSS for SMEs.

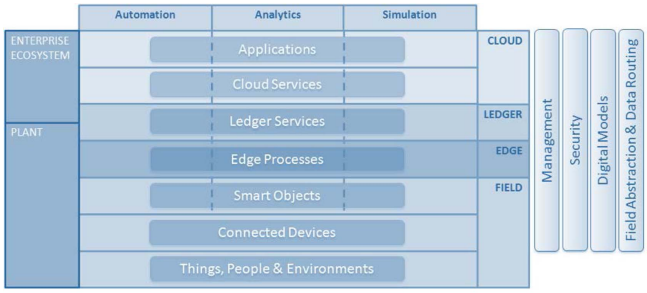
1. Requirement analysis

This section presents the requirement analysis of the technical and user-oriented aspects. The results will allow the enabling OSS for SMEs to be determined.

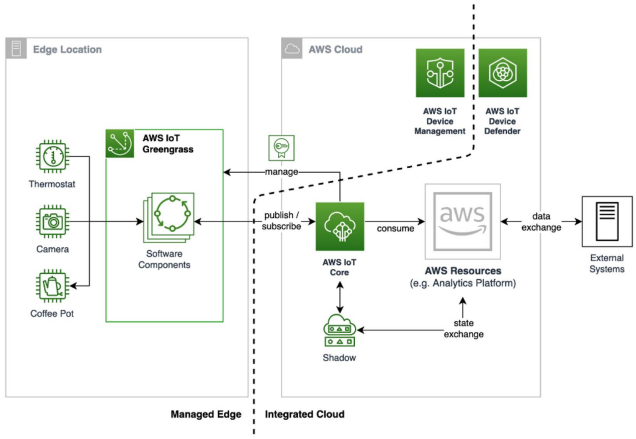
1.1 Technical requirements

Technical requirements focus on fitting industrial standards that must be satisfied to develop the necessary smart manufacturing technologies using OSS. Hence, well-established open and commercial RAs are reviewed. Figure 3 shows an example of an RA diagram. For more details, readers can refer to the official website of each RA.

- Open-source RAs: FAR-EDGE (Isaja *et al.*, 2017), Edge Computing RA 2.0 (Edge Computing Consortium, 2017), and Industrial Internet Consortium RA (IIRA) (Industrial Internet Consortium, 2017)
- Commercial RAs: Amazon Web Services (AWS) (Amazon Web Services, 2022), Google Cloud (Google Cloud, 2016), and Microsoft (Microsoft, 2022)



(a) FAR-EDGE (Isaja *et al.*, 2017)



(b) AWS IoT core (Amazon Web Services, 2022)

Figure 3. Examples of open-source and commercial RAs.

The first approach was to select an RA suitable for SMEs. Open-source RAs are easy to understand, whereas higher-level concepts are difficult to comprehend if one does not possess the prerequisite skills. Although commercial RAs provide

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useful guidance for novice developers, they require many tools and primarily focus on cloud services, not on premises. Hence, commercial RAs are unsuitable for SMEs.

Therefore, in the second approach, eight typical and necessary functional components are proposed based on the analysis of open RAs instead of the selection of suitable RAs, as follows: 1) device management, 2) communication, 3) protocol, 4) data management, 5) analytics, 6) visualization, 7 scalability, and 8) security.

1.2 User-oriented requirements

The labor and infrastructure of SMEs are considered in the user-oriented requirements to effectively define the scope of various available OSS. In general, SMEs require small technologies because of their limited use compared with large companies (OECD, 2021). In addition, they use private and on-premises for dozens of devices. However, to operate and maintain these devices appropriately, interaction functions, including control and standards for interoperability, should be considered (OECD, 2021; Prause, 2019). Table 1 lists the user-oriented requirements in addition to the functional components of the proposed small RA in the previous section.

Table 1. User-oriented requirements of SMEs for each functional component

Functional component	User-oriented requirements of SMEs
Device management	Easy to use, stable, and popular
Communication	Standard for interoperability
Protocol	Standard for interoperability
Data management	On-premises (not cloud)
Analytics	Event-driven or transfer learning (not a training of entire layers)
Visualization	Lightweight and interactive (display and control)
Scalability	Less than dozens of devices on a shop floor
Security	Private wireless/wired network (not public)

2. Enabling OSS for the proposed small RA

Previous developments of IoT-based smart manufacturing technologies using OSS are reviewed in this section. Candidates of the enabling OSS for the proposed small RA are based on an analysis of previous related studies. In addition, a recommendation for the enabling OSS is proposed based on the candidate OSS via further investigation.

2.1 Candidate for enabling OSS from a literature survey

A literature review was performed using the following search keywords: “appropriate,” “smart,” “manufacturing,” “retrofitting,” “open-source,” and “SMEs.” Consequently, more than 20 research papers were listed, but most of the results included concepts or partial implementation, and only half of them included technical details for implementing an RA. Table 2 shows the candidates for the enabling OSS based on the results. Multiple candidates were identified for visualization and data management, including Node-RED,

Table 2. Candidates for enabling OSS for SMEs

Functional component	Enabling OSS (bold: found in multiple cases)
Device management	Operating System (OS): **Linux** (Martikkala *et al.*, 2021; Nsiah *et al.*, 2018) (**Raspberry Pi OS** (Hinchy *et al.*, 2019; Kim *et al.*, 2019; Kwon *et al.*, 2021; Martikkala *et al.*, 2021; Park and Jeong, 2019; Sezer *et al.*, 2018; Waters *et al.*, 2022)) and **Windows** (Kim *et al.*, 2019; Xing *et al.*, 2021)
Communication	**Wi-Fi** (Hinchy *et al.*, 2019; Kim *et al.*, 2019; Kwon *et al.*, 2021; Park and Jeong, 2019; Sezer *et al.*, 2018; Xing *et al.*, 2021), LoRa (Martikkala *et al.*, 2021), and Ethernet (Waters *et al.*, 2022)
Protocol	MQTT (Hinchy *et al.*, 2019; Kim *et al.*, 2019), **OPC UA** (Hinchy *et al.*, 2019; Nsiah *et al.*, 2018; Park and Jeong, 2019), OneM2M (Kim *et al.*, 2019), and 6LoWPAN (Nsiah *et al.*, 2018)
Data management	Database: **MySQL** (Kim *et al.*, 2019; Nsiah *et al.*, 2018; Park and Jeong, 2019), MongDB (Martikkala *et al.*, 2021), Dropbox (Sezer *et al.*, 2018), Cassandra (Waters *et al.*, 2022)
Analytics	Image processing: Tesseract-OCR (Kim *et al.*, 2019), **OpenCV** (Kim *et al.*, 2019; Martikkala *et al.*, 2021) Complex event processing : Node-RED (Kim *et al.*, 2019), and Grafana (Park and Jeong, 2019) Machine learning: TensorFlow (Martikkala *et al.*, 2021), R (Sezer *et al.*, 2018), and Scilab (Xing *et al.*, 2021)
Visualization	Dashboard: **Node-RED** (Kim *et al.*, 2019; Xing *et al.*, 2021), **Grafana** (Martikkala *et al.*, 2021; Park and Jeong, 2019), plotly (Waters *et al.*, 2022) GUI: Qt (Kim *et al.*, 2019), Python native (Hinchy *et al.*, 2019)
Scalability	(n/a)
Security	(n/a)
Programming language	**Python** (Hinchy *et al.*, 2019; Kim *et al.*, 2019; Kwon *et al.*, 2021; Martikkala *et al.*, 2021; Sezer *et al.*, 2018; Waters *et al.*, 2022), C (Park and Jeong, 2019), and C++ (Nsiah *et al.*, 2018)

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Grafana, and Qt. Meanwhile, a few OSS were predominantly used for communication and operating systems. In addition, most OSS projects use Python and C/C++ as programming languages. Although programming languages are not a functional component of RA, they are essential for software development. Therefore, the programming language was included additionally as a functional component for SMEs.

Table 3. Recommendation for enabling OSS for SMEs

Functional component	Recommendation
Device management	Linux families are recommended for the operating system, especially for **Raspberry Pi OS**, because Raspberry Pi was used in more than 50% of the reviewed cases.
Communication	**Wi-Fi** is the most used communication method in SMEs' factory conditions.
Protocol	**MQTT** (IEC PRF 20922) is good for clouds and gateways. Also, **OPC UA** (IEC 62541) is another necessary between industrial equipment.
Data management	**MySQL** is dominant because it is reliable and widely used for several systems, although it is old. **MariaDB** is another strong candidate because it is based on MySQL.
Analytics	For image processing, **OpenCV** is the most popular and powerful one. For complex event processing, **Node-RED** is recommendable because of its easy-to-use and online services. For machine learning, the **TensorFlow** lite is recommendable for lightweight use.
Visualization	**Node-RED** is recommendable because it supports interactive use well compared to other candidates.
Scalability	There was no particular OSS found, but most OS and protocols support the basic features of these components
Security	
Programming language	**Python** is strongly recommended because it is the most popular and most OSS support Python.

2.2 Recommendation for enabling OSS for SMEs

The enabling OSS listed in Table 2 have been confirmed to be effective in previous studies; however, an appropriate recommendation with further rationale is necessitated to ease the use of OSS by SMEs. An enabling OSS is recommended herein for the proposed small RA by considering the frequency and ease of use for developing smart IoT modules with less knowledge. In addition, industrial standards are considered a top priority for communication. Table 3 presents the recommendations for each functional component. The recommendations and their references are available on a GitHub page for public access (Kim, 2022).

3. Evaluation

For the evaluation, a minimum viable product demonstration was performed to demonstrate the feasibility of the recommendations. Figure 4 shows the edge and gateway demonstration configurations for typical data monitoring. In the implementation, only the proposed small RA and the recommended enabling OSS were used simultaneously with two Raspberry Pi-based devices for each edge and gateway. The edge data were delivered to the gateway using MQTT via Wi-Fi. The gateway successfully stored the acquired data in the MySQL database and displayed the data in the form of a chart. In addition, the actions of starting and stopping monitoring were sent to the edge using the Node-RED command via a touchscreen. The implementation time including software downloading and modification was less than half a day.

4. Application scenarios

This section presents the possible application scenarios for

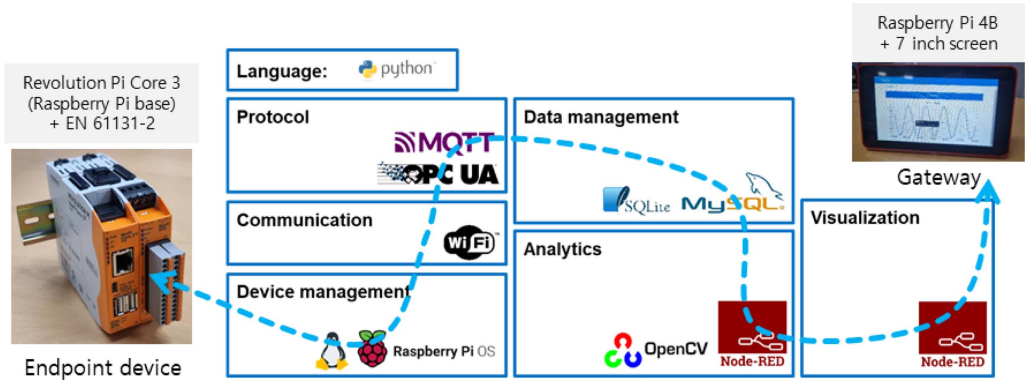

Figure 4. Diagram of the demo configuration between edge and gateway.

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practitioners in the manufacturing sector and other industries with similar requirements.

- Shopfloor environment monitoring: Owing to advances in materials and sensor technologies, various inexpensive and simple environmental sensors are available commercially. Integrating an environment sensor, e.g., a temperature of light sensor, with a single board computer (as edge computing) allows shop floor managers to monitor their workplace status anytime and anywhere (Kwon *et al*., 2021).
- Computer numerical control equipment monitoring: Recent webcams and smartphones can be used as vision sensors at production sites. Similar to the demonstration performed for the evaluation, images of the human–machine interface of legacy equipment from a webcam or smartphone can be processed in an edge computer using image processing and optical character recognition (OCR) techniques to obtain operational data (Kim *et al*., 2019).
- Process/product quality monitoring: Similar to the scenario above, the manufacturing process or product can be inspected using a simple vision sensor such as a webcam. For example, defects from fused deposition modeling and sewing stitches were detected in previous studies (Kim, Jung *et al*., 2022; Kim, Lee *et al*., 2022; Kim *et al*., 2020).

Conclusion

To facilitate the identification of user-friendly and appropriate smart manufacturing solutions for SME personnel with insufficient prior experience and knowledge, technical and user-oriented requirements for developing IoT edge computing by SMEs were compiled. Subsequently, software RAs were investigated and a literature review was performed to develop appropriate smart manufacturing technologies for SMEs. Based on the results, a small RA was proposed and an enabling OSS for SMEs was recommended. To evaluate the recommendation, a small edge and gateway demonstration with two single-board computers equipped with Raspberry Pi was performed, where some of the recommended enabling OSS of MQTT via Wi-Fi, MySQL, Node-RED, and Python were used. Finally, the feasibility of the proposed approach was confirmed by performing an evaluation demonstration.

In future studies, more technical cases involving security and scalability will be investigated. Other research results will be continuously uploaded to the GitHub page for perusal by the public and SMEs.

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