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Integrating Six Sigma into an Industry 4.0 System for Enhanced Productivity: A Case Study in CNC Processes

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Abstract

Nowaday, many manufacturing companies are integrating Industry 4.0 technology into their operational processes, particularly those aiming to enhance production operations. However, business decision-makers must remain vigilant about potential risks associated with adopting this technology. These risks include initial financial investments for testing and system installation, managing human resources to operate the new system, and concerns regarding data security. This study proposes designing an Industry 4.0 technology system to augment machining machine operations, leveraging Internet of Things (IoT) devices to facilitate connectivity and data transmission. Additionally, it aims to improve production process monitoring through visual management techniques. The machines under study are semi-automatic and lack operational digitization or expansion capacity. Through research on integrating low-cost Industry 4.0 technology into the production process, this study has achieved an annual reduction in production costs by $9593. Moreover, the defect rate for product length dimensions has plummeted from 54.90% per month to zero defects. The study employs the DMAIC method (Define-Measure-Analysis-Improve-Control) cycle within the Six Sigma methodology to investigate and apply low-cost Industry 4.0 technology to production process enhancement. This combined approach can be customized and applied to various business process improvement models, further enhancing the operation of machining machines originally equipped with Industry 3.0 technology.

Keywords

Industry 4.0; Internet of Things; Six Sigma, DMAIC; Low-Cost Manufacturing.

Introduction

The process of forming Industry 4.0 began in the late 2000s and continued to develop over the following decade. Below are the main stages in this process:

Stage 1: Initiation of the intelligent industry (2000–2010). During this period, information and communication technologies (ICT) such as the Internet, computers, and software began to be widely applied in production. Traditional automation systems have been improved by integrating new information technology components, creating more intelligent production systems.

Stage 2: Industry 4.0 (2011–2015). During this period, the term "Industry 4.0" was introduced in Germany, referring to a new industrial strategy based on information technology, manufacturing technology, automation and so on. IoT, artificial intelligence, smart automation, and wireless communications have become more important in production and management (Büchi et al., 2020; Sanghavi et al., 2019).

Stage 3: Development and deployment (2016–2020) Industry 4.0 has become a global development trend during this period. Companies and countries worldwide have focused on investing in technology and improving production processes to take advantage of the benefits of Industry 4.0. New technology applications and solutions have been widely developed and deployed in industries ranging from manufacturing, transportation, healthcare, and energy to services. In its current and future stages (2021 onwards), Industry 4.0 continues to develop and progress further.

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Technologies such as artificial intelligence, blockchain, augmented reality, and data ownership are becoming important factors in industrial development (Malik & Kim, 2020; Xiao et al., 2021).

Research into applying Industry 4.0 to factories is becoming essential to optimize production processes, increase efficiency, and reduce costs (Mehrpouya et al., 2019). Use robots and automation systems to perform manufacturing tasks. Robots can replace workers in repetitive and dangerous jobs, helping to increase productivity and ensure labour safety. Connect devices, sensors, and machines in the factory through IoT. Collecting data from these devices allows accurate and real-time monitoring and control of the production process. IoT systems can also provide detailed information about devices' status and performance, helping predict and prevent problems. Use AI and data analytics to process large amounts of information collected from sensors and systems in the factory. Data analysis helps find trends, patterns, and important information, making smart decisions and improving production processes. Use cloud services to store and share data and perform powerful calculations. This increases system scalability and flexibility, allowing remote data access and cross-platform interaction. Apply blockchain technology to provide security and reliability for transactions and processes in the factory. Blockchain can support supply chain management, traceability, and the historical storage of important information. Build a smart factory network in which devices, systems, and production processes are connected and interact. This creates a flexible, automated, self-adjusting system that rapidly responds to changing market and production requirements (Ko et al., 2020).

The digital twin is a concept in information technology, especially in Industry 4.0. It refers to creating a digitized and synchronized version of a physical system, process, or product. A digital twin can be understood as an exact digital twin of a physical object or process created by combining real-world data from sensors and data acquisition systems, along with a model, mathematics, simulation, and analysis. Essential characteristics of a digital twin include the following: The digital twin reflects the state and behaviour of a physical object or process accurately and in real-time. It is continuously updated to reflect the changes and developments of the actual audience. Digital Twin uses data analysis algorithms and mathematical models to predict, simulate, and optimize the behaviour of a physical object or process. It allows testing and optimization scenarios before executing on natural objects. The digital twin creates a strong link between the physical and digital worlds. It enables remote management and control, status and repair monitoring, performance optimization, and physical object failure prediction. The digital twin is widely applied in many sectors, including manufacturing, energy, real estate, healthcare, and transportation. It helps improve performance, reduce maintenance costs, increase availability, and create optimized solutions during operations (Fig. 1).

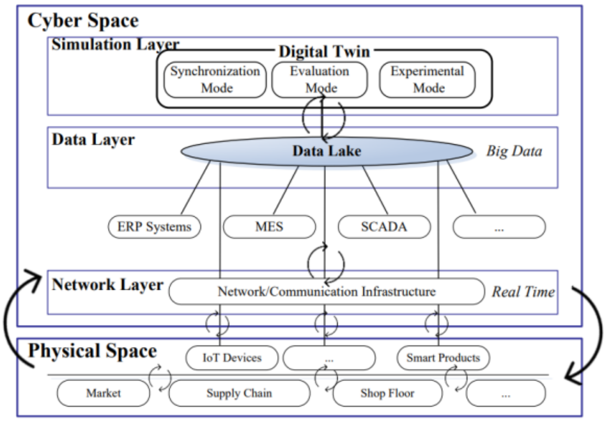


Fig. 1. Diagram of digital twin

Applying Industry 4.0 to improve manufacturing processes is an important aspect of applying digital technology and automation in industry (Nwakanma et al., 2021). Use robots and automation systems to perform production tasks. This helps increase productivity, accuracy, and process uniformity. By using the Internet of Things (IoT) to connect devices, sensors, and machines in the manufacturing process, the IoT sensors collect data on the status, performance, and working conditions of devices, allowing precise and real-time process monitoring and control. Then, data analytics and artificial intelligence process and analyze data collected from devices and processes to help find trends, patterns, and important information, making smart decisions and improving production performance. Production management system (Manufacturing Execution System, MES) to manage and optimize production processes. MES helps monitor and control manufacturing operations, schedule and assign work, manage resources and materials, and provide real-time information to monitor and evaluate performance. Use cloud services to store and share data and perform powerful calculations. This enables remote data access and information sharing across departments and organizations and provides scalability and flexibility to the manufacturing process. Build a smart factory network in which devices, systems, and production processes are connected and interact. This creates a flexible, automated, self-adjusting system that rapidly responds to changing market and production requirements. These applications help improve productivity, optimize processes, reduce waste, and respond quickly to changing market requirements. It also creates flexibility and interactivity in manufacturing while providing insights for decision support and performance analysis.

The cost of investing in an Industry 4.0 system can vary depending on the size and scope of the project, the industry, the level of automation, and the technology applied. Investment in devices, sensors, machines, and automation systems is critical. Consideration should be given to the costs of procuring, installing, configuring, and maintaining these devices. Use production management software, data analytics, artificial intelligence, factory management systems, and other technologies to integrate Industry 4.0 systems. Costs associated with procuring, customizing, deploying, and maintaining the software should also be considered. An important factor is investing in employee training to grasp knowledge and skills related to Industry 4.0 technology. The cost of training, conversion, and adaptation to new technology should be considered in investment decisions. Investing in network security, security systems, and technical infrastructure is important to the Industry 4.0 system. The costs associated with protecting data, networks, and devices from security threats need to be considered. Invest in adjusting and optimizing production processes to take full advantage of the benefits of the Industry 4.0 system. Costs associated with modifying, improving, and innovating manufacturing processes must also be considered. Businesses may need support from consulting and implementation service providers to ensure a smooth and effective implementation of the Industry 4.0 system. The costs associated with this service also need to be calculated. The total investment cost in an Industry 4.0 system can be large, depending on the scope and scale of the project. However, it should be noted that long-term benefits such as increased productivity, reduced operating costs, and improved production efficiency can contribute to reducing costs and achieving future profits (Kwak and Park, 2021; Hsu et al., 2022).

Implementing Industry 4.0 systems in small and medium-sized enterprises (SMEs) can face several limitations and challenges. One of the main limitations is the high initial investment cost to deploy an Industry 4.0 system. Investing in new technology, hardware, and software for SMEs with limited resources can be a significant challenge. SMEs often lack knowledge and skills about Industry 4.0 technologies and processes. This can increase the difficulty of implementing and managing the new system. Training or hiring employees with the right skills requires time and resources. Implementing Industry 4.0 systems requires changes in work processes and management. Some SMEs may find adapting and implementing these changes difficult, especially when the transformation requires flexibility and interaction between different departments. SMEs are often smaller in scale than large enterprises, which can cause some difficulties in implementing and taking advantage of Industry 4.0 systems. Integrating devices, sensors, and systems can require infrastructure and technical resources that SMEs may have difficulty meeting. Implementing Industry 4.0 systems poses security and data privacy challenges. Ensuring information safety and security in the digital environment can be complex for SMEs, as they have few resources to invest in in-depth security measures. However, despite these limitations, SMEs can overcome challenges by seeking support from funding organizations and technology partners or leveraging flexible and tailored technology solutions. At the same time, creating a step-by-step implementation strategy can also help SMEs effectively take advantage of the benefits of Industry 4.0.

Maintaining Industry 4.0 systems is an urgent and vital issue. Regular maintenance and repair of Industry 4.0 systems helps ensure that devices, sensors, machines, and software operate continuously and stably. This helps avoid disruptions in the production process and ensures that critical data and information are not lost. Industry 4.0 system maintenance helps optimize the performance of automated equipment and processes. Regularly inspecting, adjusting, and improving system components helps improve productivity, reduce downtime, and increase operational efficiency. Industry 4.0 system maintenance is also important in ensuring information security and confidentiality. Updating software, applying new security measures, and periodically testing systems help prevent attacks and protect important data from loss or breach. Industry 4.0 system maintenance also includes user training and support. Employees need to be trained to use and manage the system effectively. At the same time, providing technical support and answering questions helps ensure that users can use the system effectively and resolve problems quickly. Industry 4.0 system maintenance also involves technology upgrades and evolution. Software updates, upgrades, and replacing older devices with new versions help systems maintain excellent compatibility, performance, and security over time. In short, Industry 4.0 system maintenance is critical to ensure continuous operations, optimize performance, protect the security, and support users. Investing in proper maintenance helps maximize the benefits of Industry 4.0 systems and ensure project success (Fig. 2).

The Industry 4.0 system implementation rate among small and medium-sized enterprises (SMEs) may vary from industry to industry. However, this deployment rate is typically relatively low and a work in progress.

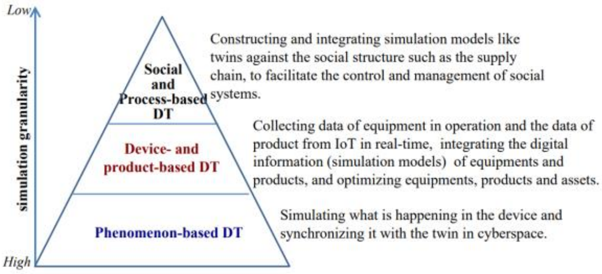


Fig. 2. Hierarchical structure of digital twins

In countries with highly developed business and technology environments, such as the United States, Germany, Japan, and South Korea, the rate of Industry 4.0 implementation in SMEs may be higher than in other countries. However, it is not yet widely available, and only a few pioneering businesses have successfully implemented this system. In economically and technologically developing countries, the rate of Industry 4.0 implementation in SMEs is often lower. Businesses in traditional industries still face many challenges regarding resources, knowledge, and investment capital to deploy this system. Industry 4.0 implementation rates may also vary by industry. The manufacturing and processing industries have higher deployment rates due to automation and complex production processes.

Meanwhile, service and commercial industries have lower deployment rates due to the different nature of work and business scale. Although small and medium-sized businesses are gradually becoming aware of the benefits of Industry 4.0 (Mehrpouya et al., 2015), actual implementation is still happening slowly. Financial constraints, technological knowledge, and change management are important in limiting this implementation rate. However, with support from organizations, governments, and technology providers, the rate of Industry 4.0 implementation in SMEs is expected to increase (Chiu et al., 2017; Ly Duc and Bilik, 2022).

The research paper is structured as follows: Section 2 presents the motivation for deploying industry 4.0 technology. Section 3 shows the application of IoT technology to Industry 4.0 technology. Section 4 presents the implementation of the Industry 4.0 prototype. Section 5 presents the operation of the Industry 4.0 technology application process. Section 6 shows the conclusion of the study.

Background

Decision decision-makers in small and medium enterprises (SMEs) may be motivated to implement Industry 4.0 systems. One of the main drivers for implementing Industry 4.0 is to improve productivity and production efficiency. By applying automation, automated processes, and smart management, SMEs can optimize production operations, reduce downtime, and increase operational efficiency. This helps increase output, improve product quality, and compete in the market. Industry 4.0 brings flexible technologies and solutions, helping SMEs adapt to rapid changes in the business environment. Deploying technologies such as the Internet of Things (IoT), artificial intelligence (AI), and smart systems helps enhance management and operations, optimize workflow, and increase production flexibility—export and supply of goods. Industry 4.0 provides opportunities for cost savings and sustainable growth for SMEs. By automating processes, optimizing resource use, and enhancing prediction and forecasting, SMEs can reduce waste, increase operational efficiency, and increase their ability to respond quickly to the market (Hamrol et al., 2019). Deploying Industry 4.0 helps SMEs compete more strongly in an increasingly competitive business environment and can expand markets abroad. Using digitalization and connectivity technologies, SMEs can provide better products and services, find new customers, and build diverse cooperation networks. Implementing Industry 4.0 is a natural response to modern technology trends. Decision-makers in SMEs may want to ensure that their businesses are not left behind in the industrial revolution and new technological trends. They may want to ensure their businesses move forward and are ready to exploit digitalization's opportunities and benefits.

In summary, decision-makers in SMEs have many different motivations for implementing Industry 4.0, including improved productivity and efficiency, improved processes and flexibility, cost savings, and sustainable, competitive growth. In the market and adapt to technology trends. This helps SMEs enhance competitiveness, adapt to the business environment, and create sustainable advantages in an increasingly growing and changing market (Nguyen et al., 2020).

Implementing Industry 4.0 can help SMEs expand their markets abroad and find new customers (Hsu et al., 2020). Here are some ways that Industry 4.0 can assist in expanding markets and finding new customers for SMEs: Digitalization and connectivity technology in Industry 4.0 allows SMEs to connect with global markets (Fig. 3). Connections through the Internet and online platforms help businesses reach new customers worldwide. SMEs can create and promote their reputation through social media, websites, e-commerce, and other platforms. Industry 4.0 provides IoT and innovative management technologies, allowing SMEs to connect and interact with global supply partners. This helps SMEs expand their access to supply, find new suppliers, and penetrate international markets (Faller and Feldmüller, 2015; Saqlain et al., 2019). With Industry 4.0, SMEs can customize their products and services to meet the local requirements of foreign markets. Flexible technology and automation enable businesses to adapt to foreign markets' cultural, linguistic, and regulatory diversity, attracting new customers and creating a competitive advantage. Information technology and artificial intelligence in Industry 4.0 provide the ability to analyze data and predict market trends. SMEs can better use analytics tools to understand foreign market conditions, customer needs, and competition. This helps businesses create effective market access strategies and find new customers. Implementing Industry 4.0 enables SMEs to create unique value by combining new technologies and services. Innovation and taking advantage of new technology help SMEs create unique products and services, attract foreign customers' attention, and expand markets. Implementing Industry 4.0 helps SMEs expand their markets abroad and find new customers by connecting globally, accessing the global supply chain, customizing and meeting local requirements, distributing, analyzing the market, and creating unique value. Implementing Industry 4.0 in small and medium enterprises (SMEs) can help expand markets abroad and find new customers.

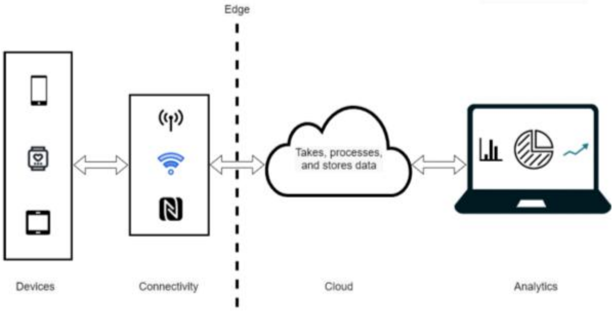


Fig. 3. Overview architecture of IoT device connection system in Industry 4.0

Raw material and Methodology

Integrating Industry 4.0 systems into the Six Sigma DMAIC (Define, Measure, Analyze, Improve, and Control) method can improve production processes. Here is how this integration can be done: Define: Use IoT (Internet of Things) technology to collect data from devices and sensors in manufacturing (Lass and Gronau, 2020; Lee et al., 2015). This helps to identify important factors and quality indicators related to the production process. Measure: Use automation systems and sensors to measure and record data in the production process. This technology helps provide accurate and continuous data on performance, quality, and other factors related to the manufacturing process. Analyze: Use artificial intelligence technology and data analysis to analyze factors affecting the quality and performance of the production process. This technology helps identify the root cause of problems and find ways to improve process efficiency. Improve: Use automation technology, collaborative robots, and smart systems to improve production processes (Tan et al., 2019). This can include optimizing production capacity, enhancing accuracy and consistency, minimizing errors and waiting times, and enhancing overall process performance. Control: using automation and control systems to maintain and control the production process after improvement. This technology helps monitor and automatically adjust key parameters, ensuring the manufacturing process maintains optimal quality and performance. Integrating Industry 4.0 systems into the Six Sigma DMAIC methodology allows for combining the power of digitalization, automation, and artificial intelligence to improve production processes. Using accurate data, intelligent analysis, and automated control enhances management capabilities and improves the efficiency of production processes.

Integrating Industry 4.0 systems into the Six Sigma DMAIC methodology in manufacturing brings many important benefits. Industry 4.0 technology enables data collection from devices and sensors in production (Osterrieder et al., 2019). This data provides accurate and ongoing information about performance, quality, and other important factors. Analyzing data through the Six Sigma DMAIC methodology helps identify the root cause of problems and find ways to improve process performance. The integration of Industry 4.0 brings forth advanced automated monitoring and control capabilities. Through automation systems and sensors, critical parameters within the production process are continuously monitored, allowing for early detection of potential issues. This proactive approach enables timely interventions to mitigate errors and unexpected downtime, thereby bolstering process stability and overall quality. Leveraging automation and artificial intelligence technologies inherent in Industry 4.0 facilitates optimized performance and heightened precision in production processes. Collaborative robots and intelligent systems excel at executing intricate and delicate tasks with more incredible speed and accuracy than their human counterparts. This not only minimizes errors but also amplifies productivity and elevates product quality.

Integrating Industry 4.0 into DMAIC methodology aids in curbing waste across the production process, encompassing time, materials, and capacity. By harnessing automation and optimization technologies, resource efficiency is bolstered while unnecessary activities are reduced, thereby fostering enhanced productivity and profitability (Lucantoni et al., 2022; Sinha and Roy, 2020). Furthermore, Industry 4.0 systems empower businesses with flexibility and swift adaptability to changes within the production landscape. With IoT technology, smart systems, and automation at their disposal, processes can be easily tailored and adjusted to align with evolving market demands, thereby optimizing competitiveness.

Adopting Six Sigma DMAIC methodology for Industry 4.0 systems yields many benefits, including heightened quality, efficiency, control, reduced waste, and increased flexibility and responsiveness. This symbiotic integration ultimately augments the production process's efficiency and competitiveness, as illustrated in Fig. 4.

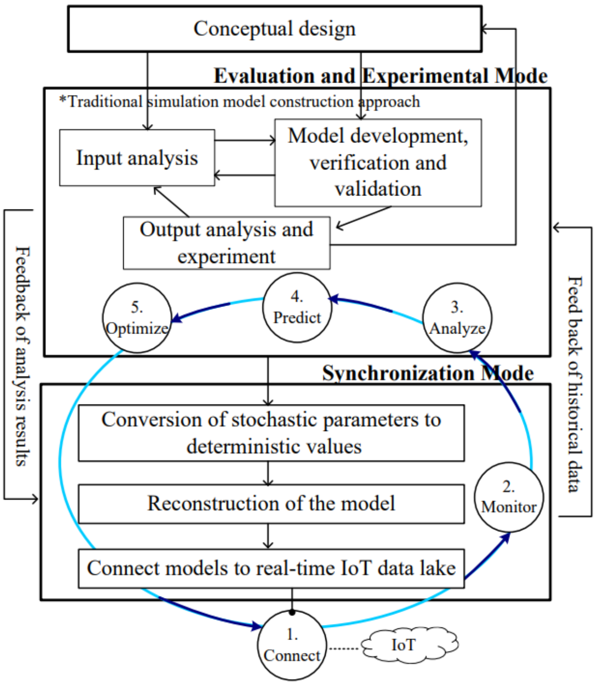


Fig. 4. Framework for digital twin

A lack of decisiveness in decision-making to deploy Industry 4.0 can significantly impact the implementation process and results. Here are some potential consequences of a lack of decisiveness in decision-making to implement Industry 4.0: Industry 4.0 brings many opportunities and benefits, such as increased efficiency, improved quality, and accelerated growth quickly (Malburg et al., 2024). However, when there is no decisiveness in making deployment decisions, decision-makers may miss opportunities and be unable to take full advantage of the technology's potential. Determination is important in orienting and determining the goals of Industry 4.0 implementation. When decisiveness is lacking, decision-makers may not have a clear plan or know how to implement the technology effectively. Implementing Industry 4.0 can bring significant and risky changes. When there is no decisiveness in decision-making, the decision-maker may be unable to evaluate and manage potential risks, causing uncertainty and difficulty in the implementation process. Industry 4.0 often involves interaction and support between systems, processes, and people. When decision-makers are indecisive, they may not make decisions regarding effective support and interaction, leading to shortages and lost opportunities to enhance efficiency and interaction in the production process. To overcome this problem, decision-makers must know the importance of decisiveness in Industry 4.0 implementation and apply effective decision-management methods. At the same time, they need to master knowledge of technology and the potential of Industry 4.0, learn real-life situations, and think strategically to make the right decisions and bring maximum benefits to the organization.

Implementing Industry 4.0 into manufacturing processes can deliver significant benefits, including increased performance, growth, and agility (Tab. 1) (Kalsoom et al., 2020). Here are some tips for implementing Industry 4.0 into your manufacturing process: First, evaluate your current manufacturing process to identify strengths and weaknesses that need improvement. Then, plan the implementation of Industry 4.0 technology based on the specific goals and requirements of the business. Use IoT (Internet of Things) technology to connect devices, machines, and systems in production. This enables live data collection and sharing, creating a federated information system and increasing automation. Apply smart sensors to monitor and measure important parameters in the production process. Smart sensors can provide real-time information about the performance, quality, and operational status of devices and processes. Use data analytics and artificial intelligence technology to process and analyze large amounts of data collected from production processes. This helps find patterns, trends, and important information to make smart decisions and improve production efficiency. Ensure employees are trained on Industry 4.0 technologies and can use and leverage new technologies. At the same time, it creates the right environment to promote acceptance and cultural change within the organization, from adopting new technologies to exploring and testing advanced manufacturing methods. Ensure safety and information security in the production process. Pay attention to data and network protection, applying appropri-

Table 1
Integrate Industry 4.0 technology in the DMAIC Method

Define phase (D)	**Measure phase (M)**	**Analysis phase (A)**	**Improve phase (I)**	**Control phase (C)**
Project Charter	Measurement and evaluation of the system	Process flow chart	Brainstorm	Suppliers, inputs, processes, outputs, and customers
Project scope	Data collection plan	Value stream mapping	Ishikawa Diagram	Capacity index
Economic analysis	Process flow chart	Cycle time analysis	5W2H	Key Performance Indicator
GRIP analysis	Reset goals and income	5 Why	Priority Matrix	Poka-Yoke
Voice of the customer	Sample	Stratification diagram	Stakeholders analysis	Checklist
Suppliers, inputs, processes, outputs, and customers (SIPOC)	Key Performance Indicators (KPIs)	Brainstorming	Investment project analysis	Standard operating procedures
	Brainstorm	Ishikawa Diagram	Gantt	The meeting
	Ishikawa Diagram	Multi-criteria fuzzy TOPSIS analysis	Standard operating procedures	**Digital numerical control**
	Statistical hypothesis testing tool		Taguchi techniques	**RFID Techniques**
			Sensor signal processing	Harmonic mitigation measurement

ate security measures to prevent attacks and security risks. Remember that implementing Industry 4.0 is a long process and requires investment in resources, skills, and management. However, if done correctly, it can significantly improve your manufacturing process's performance, quality, and growth.

The working structure of the Digital Twin in the Industry 4.0 process can be described in terms of key steps: First, data from devices, sensors, and systems in the manufacturing process is collected. This data may include information about velocity, temperature, pressure, operating status, and other process-related parameters. Data is transmitted from devices and sensors to a central system or cloud computing platform to be processed and analyzed. The collected data is processed and analyzed using artificial intelligence, machine learning, and data analytics technologies. This process aims to find patterns, trends, and information important to understanding and interacting with the manufacturing process. An accurate digital production process model is created based on collected data and information. This model is called Digital Twin, a digitalized version equivalent to the actual process. The Digital Twin is used to interact with and simulate the production process. It allows managers and engineers to inspect and test variations, options, and conditions in a safe and virtual environment. The Digital Twin provides continuous monitoring and a better understanding of manufacturing process performance. It enables early detection of problems, predicts and prevents breakdowns, and optimizes production performance. Based on information from the Digital Twin, decisions and adjustments can be made to improve the manufacturing process. Preventive measures and improvements can be implemented to achieve maximum performance and product quality. Digital Twin's organization and operations may vary depending on the manufacturing process and technologies used. However, the above structure provides an overview of how Digital Twin works in the Industry 4.0 process.

Hardware

In Industry 4.0, many devices support smart and automated manufacturing processes. Sensors are used to collect data on physical parameters such as temperature, pressure, vibration, humidity, light intensity, and others. Sensors help monitor and control production processes accurately and continuously. Embedded systems include microprocessors and embedded hardware that are directly integrated into devices and machines in the manufacturing process. They help control, collect data, and interact with networks and management systems. Wireless sensor networks connect sensors and devices via a wireless network, allowing the transmission of data collected from sensors to central systems or data collection points. Collaborative robots are robots designed to work alongside humans in a production environment. They can safely interact with humans, perform automated tasks, or assist humans in production. Cloud-based management systems provide a platform to store, process, and analyze data from manufacturing devices and processes. It allows remote access and management via the Internet. IoT devices are connected to the Internet and collect, transmit, and share data. These devices can be sensors, controls, positioning, and other production-related devices. Artificial intelligence systems are used to analyze data, create predictive models, optimize, and use machine learning to control and improve manufacturing processes. Positioning and tracking devices track the location and movement of manufacturing products, materials, and equipment. The devices above are just some common examples and are not limited. In reality, many other equipment and technologies are used in Industry 4.0, depending on the specific requirements and production processes.

In Industry 4.0 design, many cheap and popular IoT devices are used to collect data and interact with the manufacturing environment (Fig. 5). Here are some cheap IoT devices you can consider: Arduino is a popular open-source hardware development platform. It provides compact and easy-to-use boards that connect to sensors and control other devices. The Arduino can be programmed to collect data, send data over the network, and make custom requests. The Raspberry Pi is a compact integrated board with high processing capabilities. It can be used as an embedded computer to connect to sensors and send data through the network. Raspberry Pi supports multiple interfaces and connection protocols, helping integrate with other devices and systems in manufacturing. Wi-Fi modules are compact, cheap and widely used in IoT applications. The ESP8266 and ESP32 are Wi-Fi capable and can run embedded programs to collect data from the sensor and transmit it to the collection point or control system. NodeMCU is an IoT development board based on the ESP8266. It provides an easy-to-use development environment and can be programmed using the Lua language or the Arduino IDE. NodeMCU supports Wi-Fi connectivity and can integrate with other sensors and systems in manufacturing. Particle Photon is a compact IoT board with Wi-Fi connectivity. It is designed for IoT applications and supports cloud application development and remote management. The above devices are low-cost and popular in the IoT development community, and they can be used to build applications and systems in Industry 4.0 designs cost-effectively. However, when choosing equipment, consider your project's specific requirements and ensure it has sufficient flexibility and compatibility with other technologies and protocols in your Industry 4.0 system.

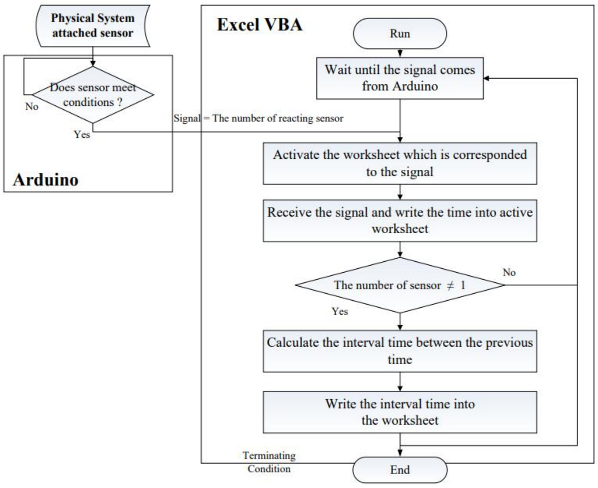


Fig. 5. The flowchart of the Excel VBA program

Among the devices mentioned, the Raspberry Pi and Arduino can integrate with other systems and devices in manufacturing. The Raspberry Pi is a powerful integrated board with high processing capabilities and support for many interfaces and connection protocols. It can connect to sensors through GPIO (General Purpose Input/Output), I2C, SPI, and UART. In addition, the Raspberry Pi can also connect to a network via Wi-Fi or Ethernet, which allows it to transmit data and interact with other systems and devices in the production process. Arduino is also a flexible and integrated hardware development platform. It can connect to sensors and devices via GPIO pins and interfaces such as I2C and SPI. Arduino supports different communication protocols through expansion modules, such as UART, Ethernet, or Wi-Fi. This allows the Arduino to interact with other systems and devices in manufacturing. Raspberry Pi and Arduino have large development communities and many documentation and open-source libraries. This makes integrating and extending their functionality with other systems and devices in manufacturing easy.

RFID (Radio Frequency Identification) systems are an important technology in IoT devices in Industry 4.0. It allows the identification and collection of data about objects through radio waves. Here are some applications of RFID systems in Industry 4.0 (Fig. 6): RFID can track and manage inventory automatically. RFID tags can be attached to products or packaging, allowing the location and quantity of goods to be identified and updated in real-time. RFID systems help improve the accuracy and efficiency of inventory control processes. RFID can be used to track and manage products during production. RFID tags can be attached to products to record information about the manufacturing process, maintenance history, technical specifications, etc. This enhances tracking and management capabilities from when the product is created until it is consumed. RFID can be used to attach components, tools, and equipment in the manufacturing process. This allows their location and status to be tracked in real time while providing information about the process and production performance. RFID enhances the ability to control and manage the manufacturing process, thereby improving efficiency and reducing machine downtime. RFID can be used to track and manage supply flows and transportation processes. RFID tags can be attached to goods, pallets, or transport vehicles, allowing their location and status to be tracked throughout the transport process. This enhances the ability to manage and monitor supply flows, thereby improving supply chain integrity and efficiency. RFID systems are important for locating, tracking, and managing information in Industry 4.0. It provides automation and enhanced management capabilities, helping improve the manufacturing process's efficiency and effectiveness.

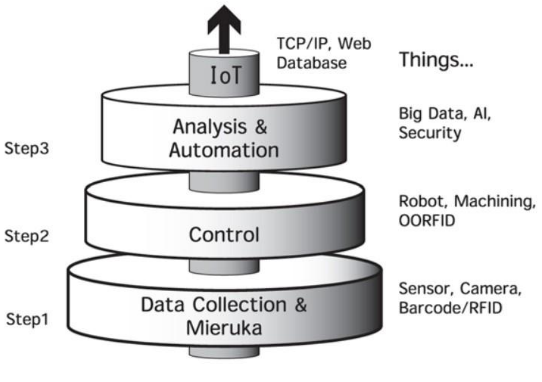


Fig. 6. Three Steps and Things in Manufacturing using the Internet of Things (IoT)

Software

In Industry 4.0 technology, embedded software plays an important role in controlling, monitoring, and interacting with devices and systems in production. Below are some popular embedded software used in Industry 4.0: The embedded operating system runs on an embedded device to manage resources, control hardware, and perform necessary functions. Popular embedded operating systems include FreeRTOS, Micrium OS, and μC/OS-II. These embedded operating systems provide task scheduling, memory management, and hardware communication features. Embedded software controls and monitors equipment and systems in the manufacturing process. They can be programmed to perform motor control, power management, signal processing, and communication with other devices. Examples of popular programming languages and development environments for embedded software are C/C++, Python, and MATLAB/Simulink. Middleware is a software layer between the application and the operating system, helping interaction and communication between components in the system. It provides protocols, interfaces, and services for connectivity, data exchange, and information management between devices and systems. Examples of popular middleware are OPC UA (Process Control Unified Architecture) and MQTT (Message Queuing Telemetry Transport). Embedded databases are used to store and manage data on embedded devices. They help store configuration, history, sensor, and operational information. Examples of embedded databases are SQLite and MySQL Embedded. In industrial environments, embedded software controls and manages robots in manufacturing processes. It includes motion programming, object recognition, interactive control, and integration with other systems. A Robot Operating System (ROS) is an example of robot control software. Embedded software in Industry 4.0 technology is important in creating connections and interactions through devices and systems in production. They enhance control, monitoring, and management capabilities and provide the basis for integrating and leveraging data in IoT systems and manufacturing processes in Industry 4.0.

Testing and deploying Industry 4.0 systems can be done cheaply by adopting some cost-effective approaches: Open-source software, such as OpenPLC, Node-RED, or MQTT. The Mosquitto broker can implement control and communication functions in Industry 4.0 systems. Using open-source software reduces licensing costs and provides a large support community. In an Industry 4.0 system, using low-cost embedded devices such as the Raspberry Pi, Arduino, or ESP32 can help reduce costs compared to using expensive industrial devices. These embedded devices are flexible and powerful enough to perform essential functions in Industry 4.0 systems. Using commonly available technologies such as Wi-Fi, Bluetooth, Ethernet, or standard communication protocols can reduce costs compared to implementing custom or proprietary technologies. This can help increase compatibility and reduce the impact on existing infrastructure. Cloud services such as Amazon Web Services (AWS), Microsoft Azure, or Google Cloud Platform can help reduce the need to invest in server hardware and infrastructure. Instead of building and managing servers and infrastructure yourself, you can use cloud services to deploy and manage Industry 4.0 applications. Seek partners and collaborate with organizations, universities, or communities providing resources and support for testing and implementing Industry 4.0 systems. These partnerships and collaborations can help reduce development costs and provide expert resources. However, it should be noted that low-cost implementation of Industry 4.0 systems may have limitations regarding features, scalability, and reliability. Therefore, a thorough assessment and clear definition of system requirements and goals are critical to ensuring that the implemented solution meets technical and business requirements.

Automation using low-cost IoT devices in Industry 4.0 in small and medium-sized enterprises (SMEs) is an important advancement to improve performance and competitiveness. Here are some methods and tips for implementing low-cost automation in SMEs: First, clearly define automation's goals and requirements. This helps focus on the most important applications and find optimal solutions at a low cost. IoT technology has developed very quickly, and many low-cost devices are available. Evaluate IoT devices such as sensors, controllers, and data collection systems to understand features, pricing, and integration with existing systems. Using open-source IoT platforms like Arduino, Raspberry Pi, or ESP32 can help save costs while providing customization and flexibility. These platforms have large community support and extensive documentation. SMEs can leverage available data from existing devices and systems to deploy automation solutions ((Chen et al., 2018). Through collecting, analyzing, and using this data, SMEs can enhance production processes' management, control, and optimization. Select specific applications to deploy automation—for example, manufacturing process automation, monitoring, maintenance scheduling, warehouse management, or energy management. Learn about IoT solutions available on the market or customize solutions to fit your SME's needs.

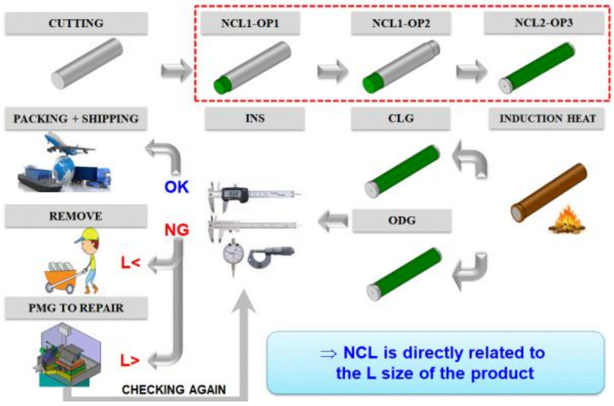
Ensure employees have the necessary knowledge and skills to work with IoT devices and automation systems. Training employees on how to use, maintain, and manage IoT solutions will help increase the efficiency and acceptance of automation in SMEs. Collaborate with other organizations, communities, and businesses to share experiences and learn about automation solutions through joint projects and affiliated networks. Thereby, SMEs can learn and apply effective methods at low costs. Evaluate the effectiveness of automation solutions and adjust and optimize if necessary. Track and evaluate performance metrics, cost savings, and process improvements to ensure that automation delivers business benefits to the SME. However, it should be noted that implementing automation in SMEs requires careful consideration of resources, techniques, and management. Before implementation, you should research, discuss, and learn about the automation solution that best suits the needs and capabilities of the SME.

Creating an Industry 4.0 model using Excel-based programming can be done using the features and tools available in Excel, such as formulas, charts, and automation functions. Here is a simple prototype to get you started: Identify the information needed for your Industry 4.0 model and design the data structure in Excel. This may include information about the devices, sensor data, manufacturing processes, and other related parameters. Use Excel formulas or connect to other data sources, such as databases or APIs, to collect data from IoT devices or other systems in an Industry 4.0 model. Use formulas and calculation functions in Excel to process and analyze the collected data. For example, you can calculate performance metrics, create charts, and perform data analyses to help you understand and manage the manufacturing process. Use automation functions and tools in Excel, such as Macros or Visual Basic for Applications (VBA), to perform automated tasks. For example, you can create buttons or automated actions to trigger processes or send notifications when problems occur. Use the chart and graphics features in Excel to visualize data.

For example, create a Gantt chart to track production processes, a bar chart, or a line chart to display sensor data and performance. Design an intuitive user interface in Excel to manage and interact with the Industry 4.0 model. You can use tools such as buttons, checkboxes, or input boxes to allow users to interact and update data. Test and tune your Industry 4.0 model to ensure accuracy and efficiency. Test and debug to ensure the model works properly and meets your requirements. Note that although Excel can be used to create simple Industry 4.0 models, it has limitations in scalability and flexibility compared to dedicated software platforms. If you are considering implementing Industry 4.0 on a larger or more complex scale, you may consider using other more suitable tools and programming languages, such as Python and C++, or open-source IoT platforms, such as Node-RED or Arduino (Fig. 5).

Case study

The machining and manufacturing process in mechanical product manufacturing (Fig. 7) may include the following steps: Identifying the tools, machinery, and equipment needed to perform the machining and manufacturing processes. Ensure that these tools and equipment meet technical and safety requirements. Ensure that the materials required to perform machining and fabrication are fully prepared and meet quality and technical requirements. Check and control the quality of raw materials before use. Conduct precision machining processes to create mechanical components to specifications. These processes may include turning, milling, grinding, drilling, casting, sandblasting, welding, or modern machining technologies such as CNC (Computer Numerical Control). Perform quality checks on machined components to ensure they meet specifications and quality standards. Use appropriate measurement tools, testing machinery, and inspection procedures to ensure product quality. After completing the machining, perform finishing steps such as grinding, surface plating, painting, or final maintenance to complete the mechanical product and achieve the desired appearance and quality. Before product delivery, perform a final quality inspection to ensure the product meets technical and quality requirements. This may include dimensional testing, functional testing, durability testing, and other criteria. Record information about machining and manufacturing processes, quality inspection results, and any issues or problems. Report and record relevant data for process improvement and quality management (Fig. 7).



⇒ NCL is directly related to the L size of the product

Fig. 7. Mechanical product line production process

In a CNC machining program, the dimensions of mechanical components are called through command codes and arguments. These command codes specify specific machining operations and arguments to determine the size and location of cuts, drilling, milling, and other operations on the CNC machine. Standard command codes in CNC machining programs include G00, the fast movement command code. Move the machine axis quickly to a specific location in the workspace. G01: Linear movement command code. Use to move the machine axis straight from the current point to the target point at a specified speed. G02/G03: The command code moves in a circular arc. Move the machine axis in a circular curve from the current point to the target point. G17/G18/G19: Command code to determine the working plane. G17 defines the XY plane, G18 defines the XZ plane, and G19 defines the YZ plane. G90/G91: Command code to determine the coordinate system. G90 defines the absolute coordinate system, and G91 defines the relative coordinate system. M03/M04: Spindle on/off command code. M03 turns on the main shaft clockwise, and M04 turns on the main shaft counterclockwise. F: Cutting-speed argument. Used to determine the cutting speed of the machining tool. X, Y, Z: Positional arguments. Used to determine the position of the machining tool on the corresponding axes (X, Y, and Z) in the coordinate system. The specific dimensions of mechanical components are determined in the CNC program using numerical values and mathematical operations. For example, to drill a hole with a diameter of 10mm, you can use the command code G01 to move the tool to the position to be drilled and then use the F argument to specify the cutting speed and X, Y, and Z to determine the position of the drill hole on the work surface.

The employee re-enters the parameters for the machining program by using a calliper type 0-500mm to measure the first product dimension and compares it to the standard size provided in the CNC process. (Fig. 8a & Fig. 8b). The operation's shortcomings have been found, even though this is done manually. These include the offset amount and parameters, which are important details.

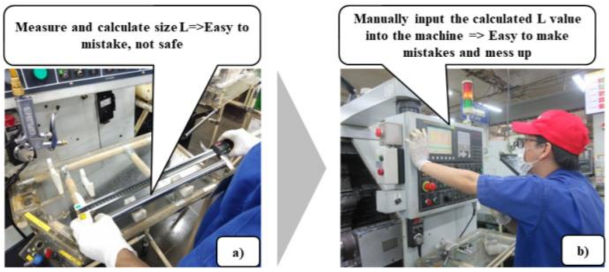


Fig. 8. a) Measure the size to confirm the offset value. 8b) Enter the offset value in the CNC machine program parameter adjustment.

Product length (L) measurements show that 54% of faulty goods have L above specifications and 22.8% have L below standards. The time frame for this is September 2021–March 2022 (Fig. 9).

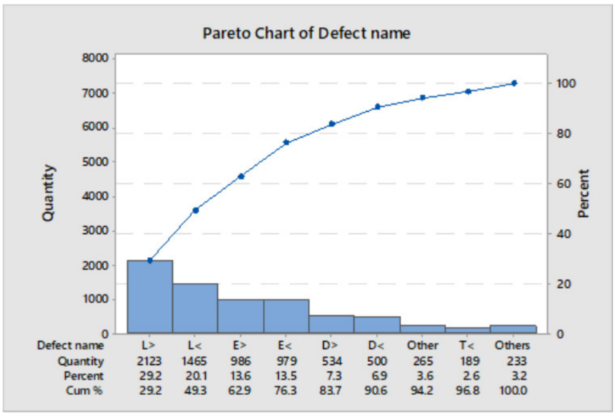


Fig. 9. Analysis of defect by Pareto

A manufacturing disturbance resulted in scraps being created at the CNC stage, with an average lead time of 9.1 days less than the intended lead time of fewer than seven days (Fig. 10). Reduced waste, increased production, improved product quality, and more customer satisfaction are the objectives of Industry 4.0 technology (Liu et al., 2022). The cutter locations are fixed in an automatic CNC machine's principal axis. The accuracy of the spindle would cause the knife cutting edge to vibrate if the wrong machining program was selected. Consequently, the tolerance standard deviation available to the machine operator is +/-0.010mm. The length dimension (L) of the product is the most important factor to take into account when it is machined. Using a 0-700mm calliper, the operator must measure a product's length and record the results in a check sheet to regulate the CNC machine's processing process.

When all three functions operate the equipment, there is a risk of waste production. Nonetheless, the machine's machining program settings were balanced using the gathered data. Operators must input the product name onto a control panel to summon the machining program from CNC (Fig. 11a). They use a 0-700 mm calliper to measure the length of the product, and they memorize the measurements. They then enter the data on a manual production control check sheet (Fig. 11b). Staff members could remember the dimensions of the first product and how the CNC machine operated in order to input parameters that needed to be offset into the control panel screen (Fig. 11c). The POKA-YOKE theory states that a proper instrument is needed for all CNC machine operator operations in order to monitor, evaluate, and verify processes. According to this theory, there will not be any reaction, and there is a perfect likelihood that waste will be created during manufacturing.

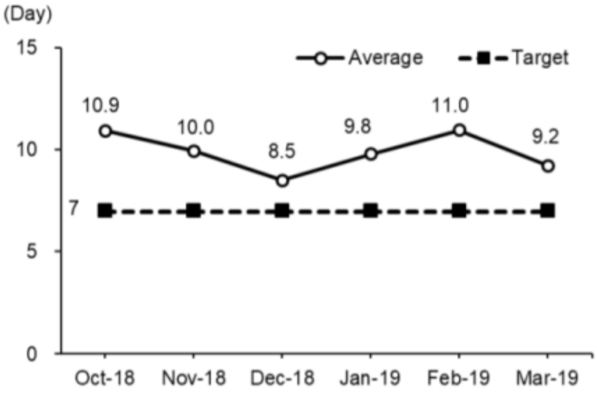


Fig. 10. Analysis of shipment data delay time

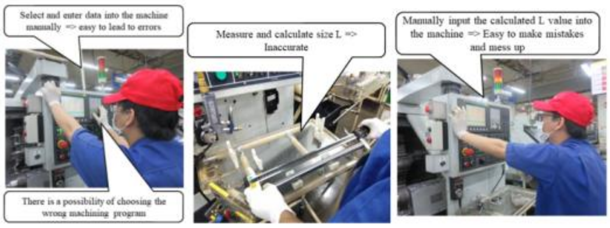


Fig. 11. Operators of CNC machines at work. a) From the screen of the manual control panel, choose the CNC machine's machining program. Utilizing 0-700mm callipers, determine the product's length and document the manual production control check sheet findings. b) Manually enter the offset parameter value for the CNC machining program on the control panel screen.

Using ERP (Enterprise Resource Planning) with RFID (Radio Frequency Identification) in Industry 4.0 can improve the production process by combining ERP with RFID, enhancing automation. RFID automatically identifies and records product, component, or equipment information during manufacturing. When combined with ERP, this information can be automatically updated and distributed to other systems and departments within the business, helping to increase the efficiency and accuracy of the manufacturing process. Combining ERP with RFID can improve inventory management in the manufacturing process. RFID accurately tracks the location and quantity of components, raw materials, and finished products in warehouses. This information can be linked and managed in ERP, helping to optimize supply processes, forecasting, and production planning. ERP can track and record production processes and quality information using RFID to label products and components. By recording data from RFID, ERP can analyze and evaluate production performance, identify problems and errors in the process, and thereby propose measures to improve and enhance product quality. When ERP and RFID are combined, information about manufacturing processes, inventory status, and customer requests can be integrated and analyzed to optimize production processes. ERP can use data from RFID to create flexible production schedules, allocate resources, and adjust material budgets, thereby reducing waiting time and waste and increasing the ability to respond quickly to customers' requests. By combining ERP with RFID, businesses can accurately track and manage resources (human resources, machinery, and equipment) and production performance. Information from RFID can be used to evaluate employee performance and monitor and maintain equipment, thereby enhancing management and the optimal use of resources in the production process. The combination of ERP and RFID in Industry 4.0 can bring many benefits in terms of efficiency, accuracy, and optimization of production processes. However, successful implementation and integration require a specific plan and investment in technology, as well as training and process changes within the business. At the same time, the security of information from RFID also needs to be considered, and appropriate security measures should be applied to ensure data security in the production process.

Several challenges must be considered and overcome when implementing ERP and RFID in manufacturing (Fig. 12). Here are some common challenges: Implementing ERP and RFID in manufacturing processes requires a significant financial investment. The cost of procuring RFID equipment, ERP software, and appropriate infrastructure and the costs associated with implementing, training, and complying with new processes must be considered. Therefore, securing financial resources is a significant challenge when implementing ERP and RFID. ERP and RFID often require integration with existing systems and existing manufacturing processes. This can be complex and requires close coordination between different departments within the business. Integration, testing, and quality control steps must be taken to ensure that ERP and RFID operate seamlessly and effectively. ERP and RFID implementations often come with changes to company processes and culture. This requires a change in working style, adaptation, and employee acceptance. There must be adequate training and support for employees to understand and accept these changes. At the same time, leaders need to create an encouraging and supportive environment to ensure success in the change process.

Fig. 12. Enterprise resource planning (ERP)

RFID can cause data security issues. Data from RFID tags can be stolen, copied, or tampered with without proper security measures. Therefore, security measures such as data encryption, authentication, and access management are necessary to ensure information safety from RFID in production. ERP and RFID implementations require accurate data management and consistency. Data from RFID and ERP must be synchronized and accurate to ensure that production and inventory management processes are carried out effectively. Clear regulations and processes must be established to maintain data consistency. ERP and RFID implementations can encounter technical issues and support requirements related to both hardware and software. Adequate preparation and technical support are required to resolve technical issues and ensure the system's continuous operation. Implementing ERP and RFID in manufacturing requires financial investment, company processes and culture changes, data security, data management, consistency, and solving problems. Resolve technical and support issues. However, when deployed and integrated effectively, combining ERP and RFID can bring many benefits, such as increasing efficiency and accuracy and optimizing production processes in Industry 4.0.

The CNC manufacturing process uses Industry 4.0 technologies to produce cutting equipment. After selecting the cutters following the machining standards, the operator mounts them on the dock. The operator manually checks to see if the cutting tools are vibrating-fixed to the standard mound. The mound-attached blades are tightened using a digital numerical control (DNC) system, and a QR Code system is suggested to automate these two tasks (Fig. 13). This system is expected to fulfil the necessary 100N-200N requirements.

If the CNC machine operator selects the wrong CNC machining program, they must specify many related parameters, increasing the handling and production lead times. Monthly maintenance data for CNC machines shows that the machine mound's precision deviates from factory-specified accuracy by 0.007mm for

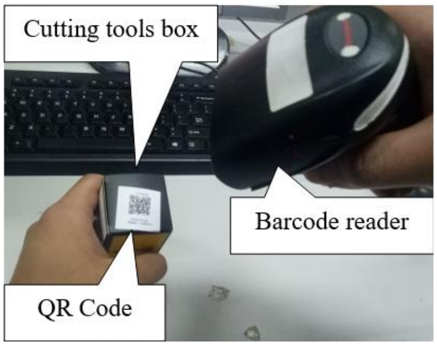


Fig. 13. QR Code system

each broken cutting tool. When the cutting tools broke every time, the machine's productivity increased to 0.005mm, and its precision increased to 0.012mm. The present work proposes the automatic configuration, testing, and application of a digital numerical control system. After measuring the product's length with a calliper, the worker records both the measurement results and the CNC machining results on the check sheet (Fig. 14). This task needs to be completed manually by the machine operator, and there are many potential risks: poor measurement, no measurement at all, erroneous recording of measurement results, failure to record measurements, and failure to measure the results. This situation requires managers to determine how to handle and control.

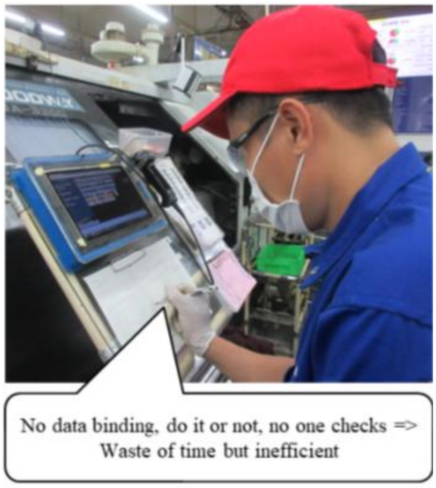


Fig. 14. Actual process control

Because measurement data monitoring product quality throughout manufacturing is not guaranteed, this study recommends testing and deploying an automated test system by linking measuring devices utilizing Internet of Things technology. Once you have measured data into the same SQL system, evaluate your measurement results using an online system. CNC machine manufacturing requires state-of-the-art power electronics and a tight integration between the hardware and controller. Less than 0.005mm should be the recommended precision for the cutting tools. Selecting and initiating a CNC machining program requires human manipulation of the control panel screen on the CNC machine. Using an algorithm communicating with the barcode reader, the SQL server is linked to the data and order names from the linked production system. The user must sequentially compare the order name data with the QR code to start the software from memory.

It would lessen the CNC machine system's dependency on the judgment and experience of its operators while enhancing robustness and efficiency. Outsourcing processes should be digitalized to improve productivity and reduce lead times for production. Industry 4.0 technology-based systems would make machines operate more efficiently and be simpler for people to use. Lowering production-related costs would also be accomplished, including those for tools, scrap, and other expenses. In contrast, Industry 4.0 technology deployments require easy-to-maintain systems that boost customer happiness and dependability, as well as consumer trust and dependability.

Regretfully, there are shortcomings with IoT-based Industry 4.0 technology systems, including slow data transfer, excessive reaction times, and inadequate data security. Some solutions were proposed to overcome these issues, such as a superior 5G information network that performs better. However, the main factor limiting their capabilities is the lost information link due to malfunctioning communication connections, which may result in delays. IoT device breakdowns were yet another possible cause of delays. Thus, to connect measurement data to an online measurement system, a screw belt and digital torque are utilized (Fig. 15), except for the SQL system, which locks if the torque measurement results are not met, the online test system instantly detects and records the cutting tool tightening force results.

An online measurement system that combines SQL and RFID can be deployed to collect data from RFID devices and store, manage, and retrieve this data through an SQL database (Fig. 16). Below is an outline of how this system could work: Use RFID devices to attach RFID tags to objects, products, or items that need to be measured. Each RFID tag has a unique code attached to the corresponding object. RFID reader devices are used to read information from RFID tags. When the RFID reader comes into contact with the RFID tag, it reads its unique code. The information read from the RFID reader is sent to the measurement

Fig. 15. Digital torque measurement system

system. This system can be special hardware or software designed to process RFID data and perform the necessary measurements. For example, it can measure time, location, or other related parameters.

Fig. 16. Measuring system according to the IoT protocol

Measurement data from the system is stored in a SQL database. SQL databases provide an organizational structure for data and allow for efficient querying and retrieval of data. Tables, columns, and relations in SQL databases can be designed to store information about objects, RFID codes, time, location, and other measurement data. The management system was developed to manage data in SQL databases. It provides functions to add, modify, delete, and retrieve data from the database. SQL management systems can also provide security and access management features to ensure data security and privacy. Applications and user interfaces can be developed to visualize and interact with measurement data from SQL databases. This allows users to view measurement information, create reports, perform queries, and perform other data management tasks. In general, online measurement systems that combine SQL and RFID use RFID to collect measurement data and store, manage, and retrieve this data through an SQL database. SQL enables efficient data management and allows applications and user interfaces to interact with the data conveniently.

The customer can define the control screen size (Fig. 17) using C# programming, Arduino control and connection tools, and measurement dimensions from the measuring system. The system screen locks, and the measurement procedure is halted if the data do not match the dimensions. The route is configured for product size tolerance in compliance with the customer's requirements. IoT solutions are investigated and implemented based on the POKA-YOKE hypothesis to improve the manufacturing process's efficiency and lower the likelihood of problems caused by operator skill deficiencies.

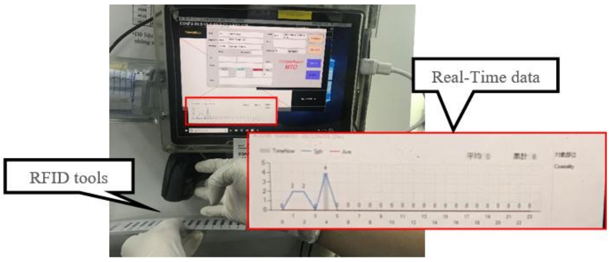


Fig. 17. Screen measuring system

To implement an online measurement system that combines SQL and RFID, you can follow these steps: First, determine the requirements for your measurement system. This includes determining the data collection type from RFID, the measurement parameters, and the data management goals. Choose the RFID device that suits your requirements. This includes selecting RFID tags, RFID readers, and other supporting devices such as antennas and processors. Design and implement an SQL database to store RFID data and measurement information. Identify the necessary tables, columns, and relationships in the database to store and manage data effectively. Develop interface software or applications to interact with SQL databases and RFID data. This includes developing functions to add, modify, delete, and retrieve data from the database, display measurement information and generate reports. Build a connection between the RFID reader and the SQL database. When the RFID reader reads information from the RFID tag, the data is transferred to a SQL database for storage and processing. Conduct system testing to ensure that reading data from RFID and storing it in the SQL database occurs correctly. Then, deploy the system in a natural environment and ensure its stability and efficiency. Ensure system users are trained to use and interact with the interface and applications. Provide ongoing support to resolve issues and enhance system performance. Note that implementing an online measurement system that combines SQL and RFID is a complex process and requires coordination between different departments within the business. Consulting experts or experienced solution providers can help you successfully implement this system.

To display real-time online measurement results, you need the following components: Use an RFID reader to read information from RFID tags and transmit data to the system (Fig. 16). Build a measurement system to receive data from the RFID reader and process it. The system can be implemented through hardware and software, with the ability to retrieve data from an RFID reader and send it to a database. Use the SQL database to store measurement data. Tables, columns, and relations in SQL databases can be designed to store information about RFID tags, measurement times, and other measurement values. Develop a user interface or application to display real-time measurement results. This interface can provide the latest and continuously updated measurement information as new data becomes available from the RFID reader and database. To display real-time measurement results, the system needs a data update mechanism. When the system receives new data from the RFID reader, it updates it to the SQL database and notifies the user interface to display the latest results. The system must update data and display results continuously to ensure real-time calculation. When new data arrives, it is processed and displayed immediately on the user interface. Thereby, users can monitor real-time measurement results on the user interface or application and receive the latest information about measurement values from the RFID device.

Industry 4.0 technological solutions in CNC production must be tested, installed, and completed quickly. Businesses can, therefore, immediately collect and keep track of manufacturing results, including successful and damaged goods, damaged and broken cutting equipment, and other anomalies. They could also assist the business in monitoring worker safety, preventing production waste, and preventing equipment malfunctions. The results indicate that if the product lead time exceeds expectations, there may be up to 54% fewer issues and a 9.1-day delivery delay rate, close to the target of 7 days. Decision-makers must approve the product Arduino boards to test and deploy this system. Production managers could closely monitor the CNC production processes to identify anomalies or risks. Manufacturing managers and decision-makers could communicate more easily thanks to Industry 4.0 technology solutions, which examine sensor data and analyze previous studies of the manufacturing process. The management board can find common trends and optimize other production methods with the help of this technology, which also improves operator cooperation, communication, and happiness. Additionally, it increases decision-makers' confidence in assessing the results of Industry 4.0 technology regarding remote work monitoring.

Discussion

Although some SME companies may use: SME companies may continue to use old machinery and mechanical equipment, they are not automated or networked. Although not as modern and flexible as new technologies, they can still help the company continue production and meet the needs of a part of the market Mishra and Kertesz, 2020). Some SME companies still use traditional production management systems, which use spreadsheets or simple software to track and manage production processes. Although they are not highly automated and real-time, they can still meet the basic needs of some SME companies. SME companies can use basic information technology, such as computers, printers, and office software, to support production (Luscinski and Ivanov, 2020). Although not technologically advanced, they can still support essential data management, storage, and processing tasks.

Real-time measurement systems in CNC (Computer Numerical Control) processes can be implemented to improve accuracy and efficiency during machining. Here are some standard real-time measurement methods and technologies used in the CNC process: Tool sensors are used to accurately measure the position and length of the tooltip or cutting tool. Through electronic signals, tool sensors can provide information about the exact position of the tool, helping to adjust and reposition the tool during machining. A tool length measurement system is a system that uses sensors and measuring devices to measure the length of cutting tools accurately. This information can be used to adjust and calibrate the depth of the cut, ensuring that the tool is operating in the correct position. Surface Height and Width Measurement systems for machining processes that require high precision of the machined surface, surface width, and height measurement system surface can be used to measure real-time response. Sensors and measuring devices will measure the height and width of the machined surface to adjust the machining process and ensure product quality. Metrology and positioning systems are precision measurements and positioning systems used to measure important parameters such as position, dimensional, and shape accuracy during CNC machining. Sensors and positioning measurement systems can provide continuous information about these parameters to adjust and ensure precision during machining. Product Inspection and Sorting System (Inspection and Sorting System) For CNC processes with high requirements for product quality, the product inspection and classification system can be used to measure and check product quality in real time. Sensors and inspection systems can automatically measure and classify products based on predetermined quality standards. Note that real-time measurement technologies and methods may vary depending on the specific requirements of the CNC process and industry. Using real-time measurement systems can help increase accuracy and ensure quality in CNC (Computer Numerical Control) (Fig. 18).

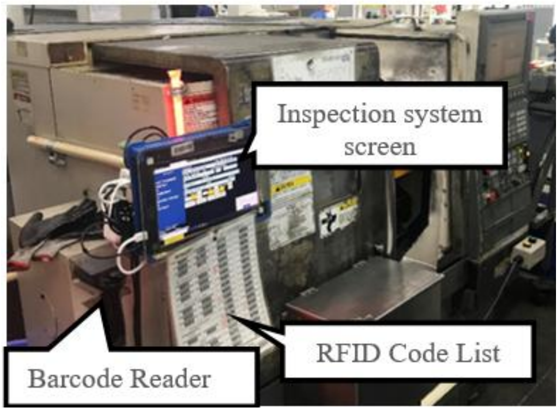


Fig. 18. Actual Industry 4.0's system in the CNC process

A working prototype for an Industry 4.0 technology solution is shown, utilizing Arduino circuits, having a minimal initial investment cost, and responding well to machines used in manufacturing. Expanding connections are needed to meet the growing demand for more connections, but continuous development costs 725 USD. Production downtime in CNC machine production is reduced to 8:00 hours by industry 4.0 technology systems that use IoT devices to install and assemble hardware for data collection quickly. System implementers can now work remotely on system design thanks to the open libraries and online data connections available in the digital world, which increases system complexity and speed of operation. Rapid testing and efficient installation of Industry 4.0 technology equipment has been completed successfully and promptly. Thanks to the effectiveness of data visualization tools, managers may now monitor and evaluate each production line's status without jumping straight into the manufacturing process. Decision-makers feel more confident in the system's deployment, testing, and implementation thanks to the representation of anomalies on real-time monitoring displays through graphs and data analysis tables. In the future, we should consider improving IoT devices and growing the system's connection. Industry 4.0 technology solutions have been applied to the production of CNC machines and have proven cost-effective, reliable, and compatible with IoT devices. Initial investment costs have also been met (Rifqi et al., 2021; Ly Duc et al., 2022). They are portrayed visually and are not limited in the kinds of data they can hold. However, the limitation faced by small and medium-sized enterprises pertains to data connectivity, as their manufacturing processes utilize outdated processing hardware and outdated connectivity devices that are either incompatible or compliant with the wrong protocol. To prevent interference with the power supply, the solution's operation must not interfere with regulating related factors such as power quality. Conclusions of the study: An entity's performance metrics and resource utilization can be measured, even while the factory's status and operations are tracked remotely via the synchronization mode of the DT. The DT's assessment mode can forecast the system's behaviours, such as entity cycle times and equipment malfunctions. The DT mode can optimize a system through scenario comparison analysis and lead time reduction, just like a typical simulation model.

Conclusion

This research outlines how a company that produces mechanical goods for small and medium-sized enterprises as a regulated organization can continuously improve its processes by assessing and integrating an affordable Industry 4.0 technology solution. The solution provided by Industry 4.0 technology digitizes the production process by replacing outdated CNC processing machines with automatic CNC machines that comply with industry standards. This helps to improve productivity, reduce waste, and realize data connections between production processes. Technology Operating Method 4.0. offers a DMAIC method-based industry 4.0 technology solution implemented through a continuous improvement process in the Six Sigma methodology. This helps production managers identify anomalies and anticipate potential hazards to create appropriate improvement plans to help lower production risks. To comply with industry 4.0 technology solutions, small and medium-sized firms adapt their processing techniques by retrofitting IoT devices. They also buy new machinery to meet their expanding production needs. The study results show that building and testing this industry 4.0 technology system is just as efficient as buying new equipment. Decision-makers will benefit from this knowledge by realizing that creating industry 4.0 technology solutions to support current manufacturing processes will come with a far lower initial cost than buying new equipment. Production managers who use a mix of old machining machines and decision-makers in small and medium-sized firms can both benefit from adding IoT devices to new equipment to boost production and operational efficiency—acquiring industry-wide testing and implementation to ensure CNC machine ongoing improvement 4.0 technology systems that create a zero defect rate for product length dimensions and a $9593 annual cost savings by greatly enhancing business and production efficiency, particularly in the production process. Extra benefits of Industry 4.0 Digital solutions include more significant customer satisfaction from deliveries made in fewer than seven days, happier employees because the manufacturing process system at the CNC process is so simple to use, and Real-time sensor data is saved into the SQL system and presented for easy viewing by all business personnel, enabling communication between new and upgraded processes. Additionally, this makes it easier for managers to assess the state of the production process in real time, spot irregularities or possible threats, and move quickly to address them.

Future research is still needed in several areas related to industry 4.0 technological solutions. First, the data security system is far from guaranteed for customers' peace of mind because there have been multiple instances of hackers obtaining user data for which law enforcement agencies have not yet developed a practical solution. Second, because the current system's high latency and limited information response speed have not yet met industry demands, researchers must develop an information network system with a quicker reaction time—system 4.0 technology. To meet the demand for skilled labour continuously improving in the production environment, the third stage is to set up a training environment where users can learn more about the industry 4.0 technology system or the communication of IoT devices. It is immediately usable by all levels of users. The fourth is that to meet the need for medium-sized and small enterprises with the least initial investment to improve their obsolete equipment continuously, manufacturers must build more IoT devices.

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