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Article

Green Smart Factory Information Transparency—Self-Healing Network Decision Analysis System

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Abstract: We proposed a management system with the concepts of decision analysis and on-site management for the transformation of the traditional manufacturing industry into smart factories (such as opaque and non-real-time information). The system was developed to achieve information transparency through a low-power customized communication protocol and make supply chain management clearer. In conjunction with the on-site management concept, it provided real-time on-site status information which integrated decision-making analysis methods to comprehensively evaluate the current situation of the factory. In the system, message queuing telemetry transport (MQTT) protocol was used to push emergency messages and quickly respond to emergencies. In this study, the system developed effectively improved the factory's information transparency, production quality and efficiency, and process optimization which were in line with ESG goals and achieved sustainable development goals.

Keywords: Scene management, Information transparency, Smart factory, ESG

1. Introduction

1.1. Research Background

In Taiwan, there are many small and medium-sized enterprises. According to data published by the Small and Medium Enterprises Division of the Ministry of Economic Affairs, there were 1.549 million small and medium-sized enterprises in 2019, accounting for 98.9% of all enterprises (Table 1). The number of employees in small and medium-sized enterprises reached 9.31 million, accounting for 80.94% of the total employment in the country (He, 2022). Among these small and medium-sized enterprises, 2.105 million people were employed in the manufacturing industry. However, due to the epidemic and the declining birth rate, these small manufacturing plants have been affected (Fig. 1).

Table 1. Number and ratio of enterprises in 2021—By number of years in business and size (Small and Medium Enterprises Division of the Ministry of Economic Affairs, 2022).

Size Category / Number of Years In Business	Total	Small and Medium Enterprises		Large Enterprise	
		Number	Ratio	Number	Ratio
Total	1,613,281	1,595,828	100	17,453	100
Less than 1 year	117,320	117,112	7.34	208	1.19
1–2 years	112,003	111,677	7	326	1.87
2–3 years	92,444	92,111	5.77	333	1.91
3–4 years	83,159	82,796	5.19	363	2.08
4–5 years	75,536	75,161	4.71	375	2.15
5–10 years	297,440	295,381	18.51	2059	11.79
10–20 years	387,069	382,909	23.99	4160	23.84
20 years (inclusive) and above	448,310	438,681	27.48	9629	55.17

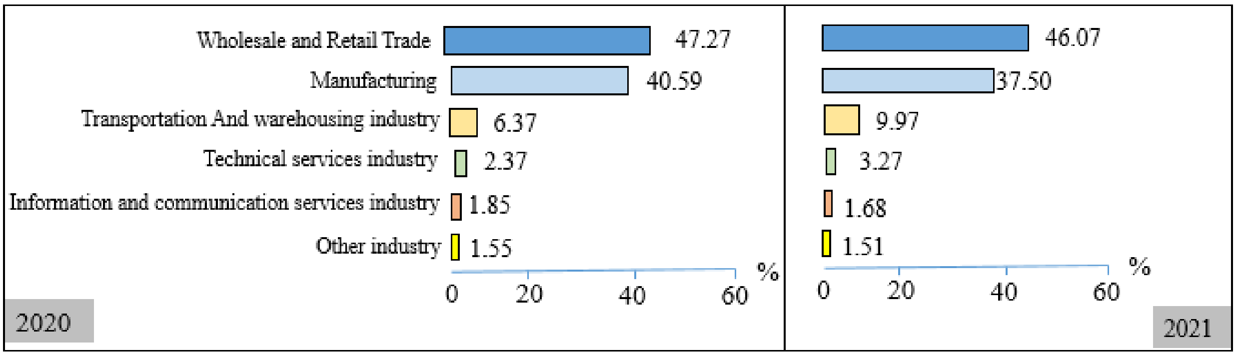

Fig. 1. Industry distribution of export volume of small and medium-sized enterprises in 2020 and 2021 (Small and Medium-sized Enterprises Division of the Ministry of Economic Affairs, 2022).

In recent years, the manufacturing industry has mostly adopted a small-volume and diversified approach to receiving orders which required frequent changes to product processing procedures to respond to changes in market demand. To keep up with the changes in the current environment, many factories have introduced machinery and equipment to assist production and deal with repetitive work-related problems. Generally, factories have problems with opaque information to prevent work processes from being optimized. Therefore, it is ncessary to plan for the transformation of general traditional factories into smart factories. The entire process followed ESG goals to achieve sustainable development.

1.2. Research Motivation

Under the dual impact of the declining birthrate and the epidemic, the manufacturing industry was facing severe challenges, especially, the trend of small and diverse orders. For traditional factories, changes in production processes are required due to order diversity. Many production processes rely on manual processing and manual inspection, resulting in frequent problems such as incorrect records, inaccurate data, and machine failures that were not handled immediately. To solve these problems, it is necessary to transform traditional factories into smart factories and introduce information transparency, scene management, and decision support systems. Recently, the environmental, social, and governance (ESG) performance of companies has been receiving market attention. There was promoted related policy and net-zero carbon emission energy consensus in response. Various industries around the world are focusing on high-efficiency production and processing, shortening Time-to-market schedules, effective energy conservation, and reducing carbon emissions, making ESG a long-term sustainable indicator of going concern (Cai, Gu, and Wang, 2022). Thus, we built a system to achieve the transparent management of factory sites while complying with ESG standards.

1.3. Purpose

Due to the advancement of Industry 4.0, factories are slowly adopting automated processes that require machines to be connected in series. At this time, the technology of the Internet of Things (IoT) is needed, and general factories enter Industry 4.0 and slowly transform into smart factories, entering the era of digital control (SEMI Taiwan, 2019). Currently, Industry 4.0 is still practiced mostly by large enterprises. Small and medium-sized enterprises were the center of the manufacturing supply chain in many countries, but they were faced with the situation that old equipment still needed to be used but lacked information and communication functions. To move towards smart production and integrate virtual and real situations, many difficulties and obstacles for many small and medium-sized enterprises must be overcome (Li and Lai, 2019). Traditional factory production lines often required manual registration and inspection to make the production process slow and error-prone. Thus, the factory introduces mechanical equipment and IoT systems to achieve information transparency and support production with real-time data. To transform the traditional manufacturing industry into a smart factory, we proposed a management system for information transparency to incorporate decision-making analysis and scene management concepts and create a management system that meets ESG goals. Using the decision analysis method, we explored the current situation of the factory and identified key factors to improve information transparency. At the same time, scene management concepts were used to optimize production processes, energy conservation, sustainability, and environmental benefits.

2. Methods

2.1. Research Questions

The global epidemic and the trend of declining birthrate have prompted the manufacturing industry to explore how to use remote collaboration and reduce cross-factory and cross-border working hours and energy consumption. This was also related to energy conservation and carbon reduction as a core capability of the manufacturing industry (Liang, and Lin, 2022). We investigated the problems of transforming traditional factories into smart factories and developed a set of methods to deal with these problems. Thus, the focus of this study was put on a single plant with an emphasis on concentrated research scope and testing which strived to make the traditional factory environment simpler and more transparent and integrate information transparency, scene management, and decision support functions into the system. At the same time, we explored how to reduce the production process and the response time for accidents to improve the process using the IoT technology for remote control. As factory information security was also extremely important, smart factories use many IoT technologies and devices, and through the connections between these devices, a large amount of data is transmitted into databases, which contain confidential information and operations. Accordingly, there are many cyberattacks to steal the data which affects the operation of the factory. The following were the problems compiled according to Yang (2022) in the transformation of traditional factories into smart factories which we mainly focused on in this study.

(1) Resource waste and energy consumption: There was a waste of resources in traditional factories. One of the main reasons was the lack of real-time data monitoring and analysis. In this case, the production process was adjusted in time to produce according to actual demand. This leads to overuse of materials such as waste of raw materials, electricity, and water.
(2) Lack of production process records: It was often difficult for traditional factories to comprehensively record past production processes, mainly due to the lack of appropriate production data recording systems. Therefore, it was not possible to easily compare past and present production status and to know exactly how quickly production is progressing.
(3) Manpower shortage and production efficiency issues: Traditional factories were often plagued by manpower shortages and low production efficiency, because of repetitive tasks in the production process, lack of automation, and insufficient staffing. This results in delayed lead times and inconsistent product quality, as the production process is susceptible to interference from human factors.
(4) Data security: Smart factories require the use of IoT devices, and the connections between devices transmit a large amount of data to the database, which contains confidential information and operations. If it is attacked or stolen, it will affect the operation of the factory. Data security has become extremely important. These devices and the transmission of data must be secured to protect confidential information from threats.

2.2. Solution

A smart factory was not an unmanned factory. All machines were connected through mechanical equipment and IoT technology. To make factories smart, not only did the equipment need to be automated, but the data flow of the software must also be automated. Thus, management must generate automated functions through software and hardware (Wu, 2020). The core of a smart factory is a production system that integrates modern technologies such as the IoT, big data, automation, and robotics. These technologies enable the manufacturing process to generate large amounts of production data, enabling decision-making and flexible production planning. These characteristics prompt traditional factories to transform into smart factories to solve the problems encountered by traditional factories. In a smart factory, modern technologies such as the IoT, big data, and automation are integrated. These technologies are used together on production systems to generate a large amount of valuable data. Collected data through information transparency are used to support decision-making, optimize production plans, and cooperate with scene management control to achieve flexibility in the production process. The problems associated with such characteristics faced by traditional factories in transformation and the solutions were proposed by Yang (2021). He also suggested how small and medium-sized enterprises were successfully transformed. In this study, the following three points were considered important.

2.2.1. Information Transparency

At the production site, the most common problem is not knowing the production status or being unable to handle emergencies on the assembly line promptly. It is not possible to produce only one type of order in a factory so it is important to know how to deal with the abnormalities of different products timely. The systems with high transparency often require smooth node connections and clear data. Completed and accurate data recorded from the supplier's raw material procurement to the customer's sales data are demanded (Guo, and Tang, 2022). Information transparency brings convenience to the factory by reasonably allocating personnel and raw materials. The transparent system helps management better understand production status discover bottlenecks in time and optimize them to improve production efficiency. The following were key features of the information transparency system architecture designed in this study.

(1) Clear production progress: The system accurately presents the factory's output and production progress. It helps management accurately control time and raw material input to quickly adapt to changes in market demand and improve production efficiency.
(2) Troubleshooting of abnormal conditions: A transparent system promptly detects quality problems in the production process, so that measures are taken quickly to deal with them and improve product quality. At the same time, losses are reduced and management is informed of production costs and inventory status on time so that they can adjust production-invented strategies and reduce waste.
(3) Machinery working hours: The system collects machine running time data to determine the machine's working hours. If the machinery is running for too long, it means malfunctioning or overheating. Supervisors stop machines based on the data, thereby extending the service life of the machinery.

2.2.2. Operation of Scene Management

Scene management refers to the effective management and coordination of resources, manpower, and time factors in the actual work site. To ensure production efficiency, quality, and safety (Table 2), the main elements of scene management are required including staff (workers, managers, etc.), machines (equipment, tools, etc.), materials (raw material, processed material, etc.), environment (noise, vibration, etc.), and information (machine parameters, work arrangements, etc.) (MBA Think Tank Encyclopedia, 2009) to carry out reasonable and effective plans. Further, it is required to improve efficiency and quality through data analysis and automation systems. A supervisor is usually responsible for Scene management, which requires a comprehensive understanding of on-site conditions to effectively organize and guide employees to ensure the smooth progress of production operations.

Table 2. Elements and purposes of scene management (MBA Think Tank Encyclopedia, 2009).

Scene Management Elements	Purpose
Staffs (Workers, managers, etc.)	The configuration of managers, workers, and other personnel ensures productivity and efficiency on-site
Machines (Equipment, tools, etc.)	Machines and equipment at the production site, including use, maintenance, overhaul, and upgrades, ensure the normal operation and production efficiency of the machinery and equipment
Materials (Raw material, processed material, etc.)	Raw materials, products, semi-finished products, and tools, including storage, control, and quality assurance to ensure the quality and timely supply of materials
Environment (Noise, vibration, etc.)	The safety, cleanliness, maintenance, and environmental protection of the production environment, including noise, vibration, and temperature, ensure the health and safety of the production environment
Information (Machine parameters, work arrangements, etc.)	Information management, production progress tracking, product quality management, production cost control, work arrangements, manufacturing resource planning, and equipment maintenance

2.2.3. Proactive Notification of Decision Support

Usually, the traditional factories require supervisors or employees to check the production progress and machine operation, or actively check records by using methods such as swiping barcodes. Problems occur when they do not understand the operating status of the factory. All machinery and equipment in a manufacturing environment are shut down for a while for routine preventive maintenance procedures. These periodic procedures are performed for necessary routine maintenance to prevent catastrophic or long-term failures (Creehan, 2005). Therefore, sensors are installed on the machines and continuously collected data to provide a clear understanding of the current status of the production line. In addition, the supervisor keeps observing current situations through a notification on mobile phones. In on-site management, proactive notifications effectively must be provided to prevent machine damage and loss of raw materials. By comparing current data with historical records, managers gain an in-depth understanding of production status, making it easier for them to grasp production conditions. These features provide specific and practical solutions to various challenges encountered in the transformation process of traditional factories. The three major features include information transparency, scene management operations, and proactive notification of decision support. By realizing information transparency, the transparency problem in the production process was solved, making the production process visible and controllable. By strengthening scene management, resources are allocated more effectively to improve production efficiency and reduce risks. Proactive notifications are required for decision support, grasped production status on time, and responded quickly to improve production flexibility.

2.3. Connection Method and Hardware Selection

To cope with the situation, many problems can be solved through IoT technology, such as how to flexibly change production products and know the production progress in real-time. The above issues are dealt with to improve information transparency. Using transparent information, the progress becomes clear to proceed to the next process more accurately. However, to make information transparent and allow information to flow between devices, it is necessary to choose the IoT connection method and hardware. There are many connection methods and hardware on the market, such as Wi-Fi, Bluetooth, and ZigBee. These are currently the most commonly used ones in the factory. The following introduced the common communication protocols on the market and introduced their advantages and disadvantages respectively (Wang, 2022).

(1) Bluetooth Low Energy: The main features of low-energy Bluetooth are low power consumption and an automatic wake-up mechanism. These allow for operating for a long while saving energy. However, Bluetooth has a small coverage range and a limited number of devices that are connected at the same time, which makes it ineffective in large factories. Bluetooth Low Energy usually supports the simultaneous connection of a small number of devices. In factory operation, it does not support the connection of all devices. Moreover, the transmission rate of Bluetooth Low Energy is slow, which limits the application scope.

(2) ZigBee: ZigBee is a communication protocol suitable for industry. It has the characteristics of low complexity, low cost, low power consumption, and low speed. It enables self-organized network nodes to communicate with a large number of devices. However, ZigBee only senses and controls, so the amount of information transmitted is limited. In terms of power saving, it is more efficient than low-energy Bluetooth. However, ZigBee's output distance is relatively short, and a repeater is required to extend its coverage. Therefore, it is not suitable for use in factories with larger areas and is difficult to develop and the cost of the product was also relatively expensive.

(3) Wi-Fi: Wi-Fi is characterized by high speed, wireless data transmission, convenience and fast, and a large coverage area. It is used for a wide range of data transmission needs within factories. The technology is mature and highly popular. Many devices support Wi-Fi. Including mobile phones, tablets, and computers. Since factories usually require higher bandwidth and higher data transmission speeds, Wi-Fi technology allows for higher transmission speeds and better device interconnection. However, Wi-Fi devices have relatively high power consumption and usually need to be connected to a power source, affecting the energy-saving in the factory. IoT devices usually need to be connected to the network and communicate with other devices and systems. If the network is not secure, such as an unencrypted Wi-Fi network, data can easily be stolen or modified during transmission.

For factories, Wi-Fi's wide coverage, fast transmission rate, and relatively low cost are advantages. However, data security and energy consumption need to be considered. Although Bluetooth has the advantages of low energy consumption and ease of use, its coverage is small and the number of devices it supports at the same time is limited. Therefore, it is not suitable for industrial applications. ZigBee has the advantages of low complexity, low cost, low power consumption, and self-organizing network nodes. It supports the connection of a large number of devices. However, the transmission rate is low, repeaters are required, the development difficulty is high, and the product cost is also higher. In a comprehensive comparison, considering that factories need to transmit environmental and equipment parameters within a wide range, the Wi-Fi communication protocol is more in line with the requirements of this study (Table 3).

Table 3. Comparison of communication technologies (Wang, 2022).

Parameters	Wi-Fi	Bluetooth Low Energy	ZigBee
Power consumption	X	O	X
Transmission distance	O	X	O
Safety	X	O	O
Number of supported devices	O	X	O
Development difficulty	O	O	X
Transmission rate	O	X	X

Characteristics suitable for this study O; Characteristics were not suitable for this study X.

2.4. Network Connection and Active Push

Although traditional Wi-Fi has the advantages of long transmission distance, support for multiple devices, easy development, and fast transmission speed, it also demands high power consumption and information security risks. To overcome these problems, we adopted a protocol similar to Wi-Fi functionality, namely ESP-Now. The ESP-Now protocol has similar advantages to Wi-Fi, such as long-distance transmission, low latency, and support for a large number of devices broadcasting simultaneously. In addition, ESP-Now also has the characteristics of low energy consumption and meets the requirements of energy conservation and carbon reduction in ESG. To ensure information security, we used a Bridge to distinguish internal and external networks to prevent the leakage of sensitive data. ESP-Now was used as the communication protocol for transparent information and active data collection, while message queuing telemetry transport (MQTT) was used as the active push protocol. It was realized real-time data reception and combined with the ESP-Now protocol to achieve efficient data transmission. This study used ESP-Now to achieve real-time data transmission, while MQTT was used to actively push machine exception messages.

(1) ESP-Now: ESP-Now has a fast speed, low latency, and low-power wireless transmission technology. Its functions are similar to traditional Wi-Fi. However, ESP-Now allows for instant device interconnection without connecting to a wireless access point. In addition, ESP-Now communication is point-to-point, so if the single-chip microcontroller is suddenly powered off or reset, it is automatically reconnected to other paired controllers. The following are the advantages of ESP-Now (Huang, 2023):

- Low latency: ESP-Now's transmission latency is very low and reaches millisecond-level fast transmission.
- Low power consumption: ESP-Now has low power consumption and reached a low power consumption mode of about 200uA.
- Easy to implement: The construction of ESP-Now is simple, requiring only two single-chip microcontrollers to communicate through a simple API interface.
- High reliability: ESP Now's transmission is based on Wi-Fi technology and has high reliability and stability.

(2) MQTT: MQTT was a lightweight protocol designed for IoT technology. This technology requires very low network bandwidth and is suitable for use in IoT environments with low power consumption and limited bandwidth. It transmits messages in real-time (Cubie, 2017). This protocol was used to actively push broadcasts when machine abnormalities or emergencies occurred in this study.

We combined the two communication protocols ESP-Now and MQTT applied them to the system and realized the requirements of information transparency and device connection through ESP-Now. At the same time, through the active push function of MQTT, real-time notification of abnormal events was provided to correspond to the characteristics and goals of transforming traditional factories into smart factories.

2.5. Scene Management

Traditional factories have difficulties in data collection. Raw data are often disorganized and difficult to classify or identify their sources and purposes. To solve these problems, we applied the concept of scene management by subdividing the traditional factory into five clear blocks (Fig. 2). These five present staff, machines, materials, environment, and information. The proposed system classified and managed machines.

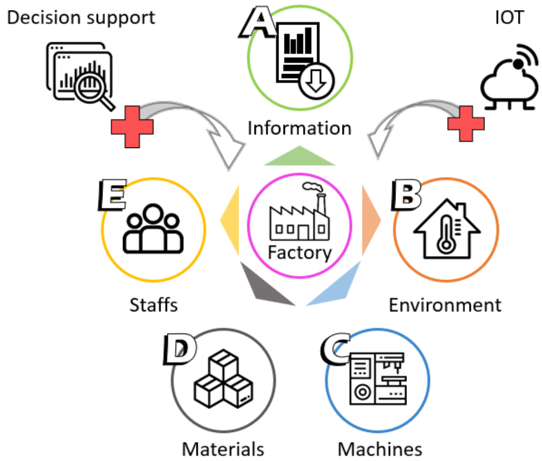

Fig. 2. Five blocks (ABCDE) of scene management.

(1) Information classification (Fig. 2A) was conducted for all aspects of information management, production progress tracking, product quality management, production cost control, work arrangements, manufacturing resource planning, and equipment maintenance.
(2) Environmental classification (Fig. 2B) was conducted for the safety, maintenance, and environmental protection aspects of the production environment. Including managing noise, vibration, and temperature to ensure the safety of the production environment.
(3) Machines classification (Fig. 2C) was conducted within each block, machines to identify each machine and ensure that its operating status can be monitored.
(4) Materials classification (Fig. 2D) was conducted for raw materials, products, semi-finished products, tools, etc and material storage, control, and quality assurance to ensure the quality and timely supply of materials.
(5) Staff classification (Fig. 2E) was for the management of the human resources of the factory, including the configuration of workers and managers. Ensuring proper distribution and effective management of personnel is critical to improving productivity and efficiency on site.

The segmentation and classification were carried out to provide a clearer structure for factory operations. Decision support and IOT technologies were also added to this system to make the structure more complete, the data collection more targeted, and the transparency of information. Managers were more easily identified and resolved production issues within each block. This improved the overall operational efficiency, overcame the difficulty of data collection in traditional factories, and promoted the transformation of smart factories.

2.6. Decision Support

Traditional factories faced difficulties in data collection and analysis. They lacked real-time data, and the data were scattered and not transparent, making the decision-making process complicated (Guo, Jiang, Chen, and Liu, 2004). We incorporated the concept of decision analysis to provide factory managers with more real-time and accurate information data and integrated past production records into a database for in-depth analysis and process optimization. There were key features of how decision support systems helped overcome these problems.

(1) Real-time visualization was adopted to provide real-time production data and visual presentation, allowing managers to quickly understand the real-time status of the factory. There was immediacy and visualization helped managers react quickly and adjust production plans to respond to changes in market demand.
(2) Predictive analysis was carried out by collecting machine information and comparing it with past data to determine possible production problems or machine failures and enable managers to take preventive measures in advance to reduce production interruptions and cost losses.
(3) Intuitive data visualization was adopted to present analysis results and produce data to managers in an intuitive way. It also provided graphics to understand data easily, allowing managers to quickly grasp key information.

(4) Data comparison and verification were carried out to query records and compare them with current data, eliminating possible errors caused by manual comparison, ensuring accurate data verification, and helping managers make the best decisions.

The decision support was used to solve the data comparison and decision-making problems faced by traditional factories. It provided real-time, integrated, and visualized data, supported predictive analysis, improved information transparency, and automatically performed data comparison, thereby helping managers make decisions more conveniently.

3. Results and Discussions

The proposed system contained three core ideas (information transparency, scene management, and decision support), and four major features determined based on these ideas (low-power self-healing network, information transparent scene management, data analysis, and decision support and emergencies were pushed immediately) (Fig. 3). Decision analysis methods were used to comprehensively evaluate the current status of factory production and identify the key to improvement through scene management concepts. Supervisor information was provided to effectively allocate production lines and personnel movements to optimize the production process to reduce energy consumption and improve sustainability and environmental benefits. The four major features of the system are described as follows.

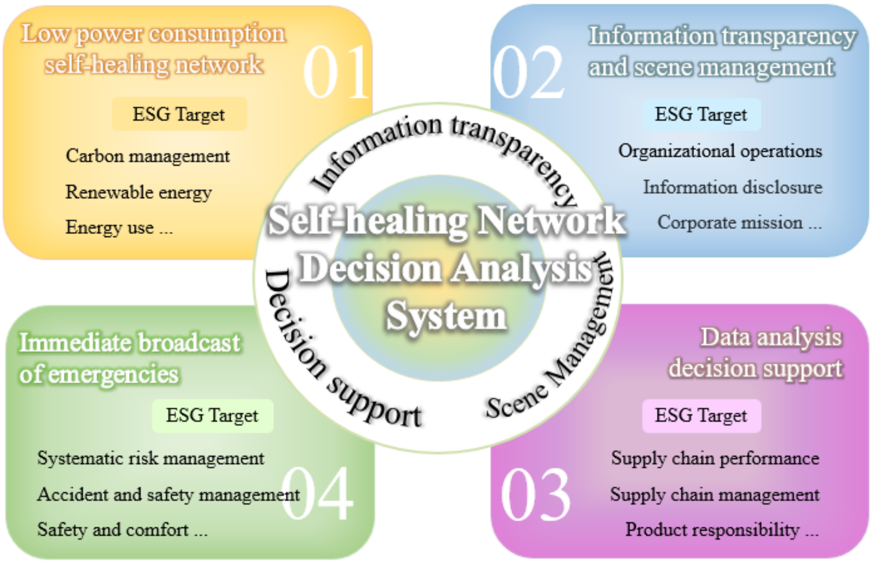

Fig. 3. Three core ideas and four features of information transparency in green smart factories.

(1) Self-healing network: In the past, factories usually used a more traditional way of transmitting information. Mostly wired or wireless connections, without proper sensors. Equipment fails were not discovered immediately. By connecting devices through the concept of the IoT and using a customized ESP-Now communication architecture (patent application approved, Patent No. M645790), the proposed system offered the advantages of low power consumption, fast pairing, multi-connectivity, and self-healing. Due to the characteristics of the self-healing network, when a device failed to connect, it automatically formed a new connected network. It determined which machine was faulty and helped managers allocate employees as soon as possible to reduce costs and improve efficiency.

(2) Transparent scene management: Based on the concept of scene management, the proposed system provided real-time monitoring (such as equipment operation information, decision support analysis information, equipment abnormality warnings, and immediate process changes) for information transparency and intelligent management of the factory. Through this information, the competent authorities managed the factory assembly line process and rationally mobilized personnel to deal with the situation.

(3) Analysis and decision support: The concept of decision analytics was used to provide managers with more real-time and accurate information data, compiling the records into a database, analyzing the records, optimizing the process, and supporting them in making the best decisions in the production process. Managers queried the data through a dedicated page, and the analytical information on the page was presented on the query page so that managers could easily understand the current situation and make decisions based on the recommended optimization results.

(4) Immediate broadcast of emergencies: Real-time monitoring allowed for checking machine status and using environmental parameters anytime, anywhere without having to travel to the plant. In terms of information on equipment operation, microcontrollers and sensors were installed on machinery and equipment to collect information on power consumption and running time of the equipment. The data was transferred to a database where the proposed system predicted the operational status of the equipment and provided it to the plant management for querying. When an abnormality occurred in the device, the microcontroller determined the abnormal situation (edge computing) and sent an immediate warning message to relevant personnel through the MQTT protocol to handle the problem on time.

3.1. Low-power Self-Healing Network

In traditional factories, the common star topology connection method is prone to the failure of a major node which halts the whole system. The wireless star topology requires multiple nodes to fully cover the factory area. In contrast, we used a customized network structure, which is a customized architecture ESP-Now forms a connected network automatically with low energy consumption. In the proposed system, each device was considered as an independent node connected to form an overall network. If a node failed, other devices automatically searched for the nearest node to form a connected network to keep data transmission uninterrupted and ensure smooth transmission (Fig. 4). Since the customized structure has network self-healing characteristics, the reliability and stability of the system were improved. Even if a single node failed, the entire system operated, avoiding production interruption and data loss. Due to the self-healing nature of the network, the complex deployment of a star topology was not required, making the expansion and management of the system simpler and more efficient.

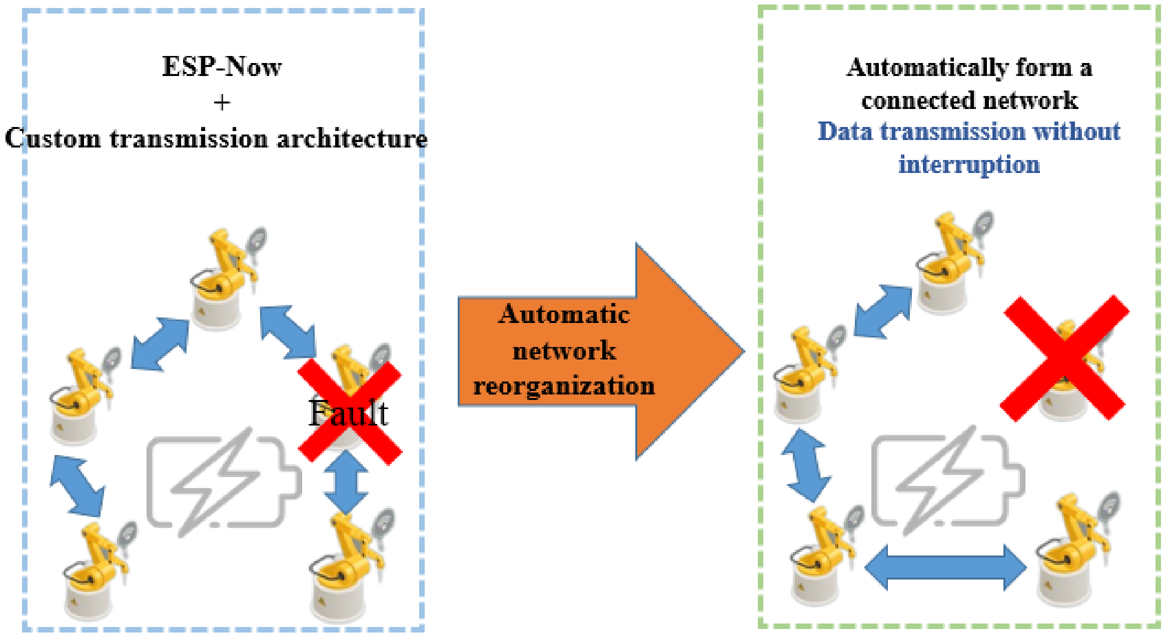

Fig.4. Automatic reconnection for equipment failure.

3.2. Information Transparency and Scene Management

We integrated the core concepts of scene management into factory operations, focusing on the five elements of staff (workers, managers, etc.), machines (equipment, tools, etc.), materials (raw material, processed material, etc.), environment (noise, vibration, etc.), and information (machine parameters, work arrangements, etc.) (Fig. 5). The factory data was organized by the aforementioned classification. In this study, a customized web interface (Fig. 6) was used for users to view the relevant information in real-time and track the energy consumption and waste during product production on time to solve the problems of opaque information and lack of real-time availability. When using the network within a factory, extra attention was paid to information security, especially when highly confidential data was stored in the factory to avoid being stolen or altered. The factory architecture was distinguished into an internal network and an external network. The intranet was used for data transmission through a low-power self-healing network to ensure the security and stability of the data in which a certified change management professional (CCMP) (counter mode (CTR) with cipher block chaining-message authentication code (CBC-MAC)) was used to protect the data while ensuring the integrity and authenticity of the data. In the external network, bridges were used to convert protocols and detect unusual activities and intrusions, further improving security. Through clear classification and real-time monitoring, the problems of information opacity and insufficient timeliness were eliminated. At the same time, multiple strategies were adopted in terms of network security to ensure the confidentiality and integrity of data.

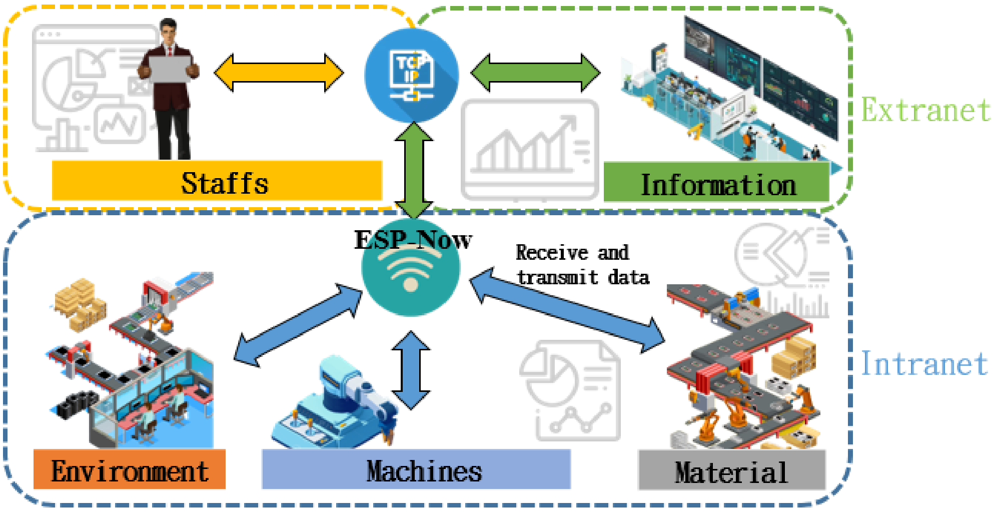

Fig. 5. Scene management information transparent architecture diagram.

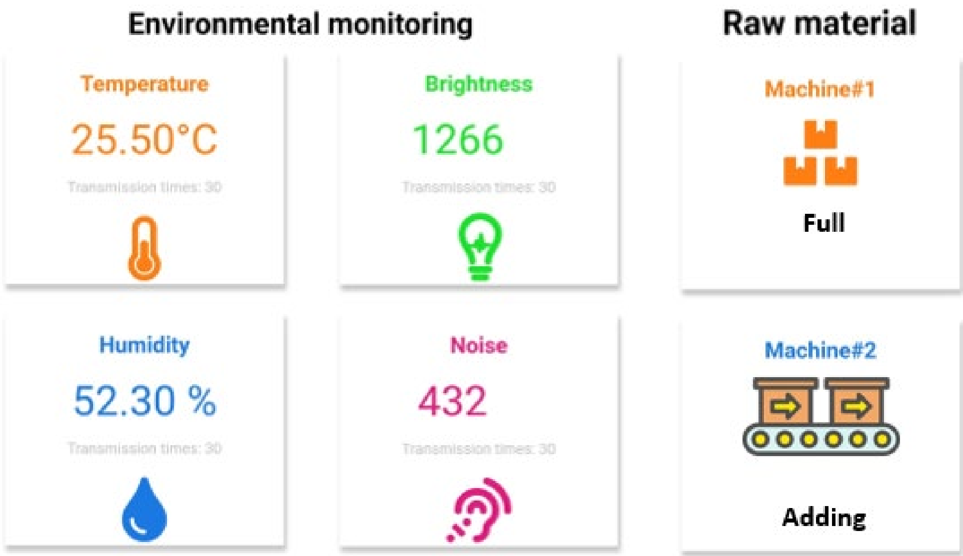

Fig. 6. Dedicated web interface.

3.3. Data Analysis and Decision Support

We collected the status parameters of machines or equipment at the factory site and stored these parameters. The system predicted possible upper and lower bound values based on changes in these historical parameters (Fig. 7). Once the system detected that a parameter was higher or lower than the preset range, the system determined it as an abnormality and notified the manager of the relevant situation immediately (Fig. 8). There was a slow production speed of the assembly line in the factory for example if the production rate of a zone differed too much from the time of the last production. In this case, the proposed system analyzed the equipment data to detect anomalies (Fig. 9) and alert management, while minimizing potential production interruptions.

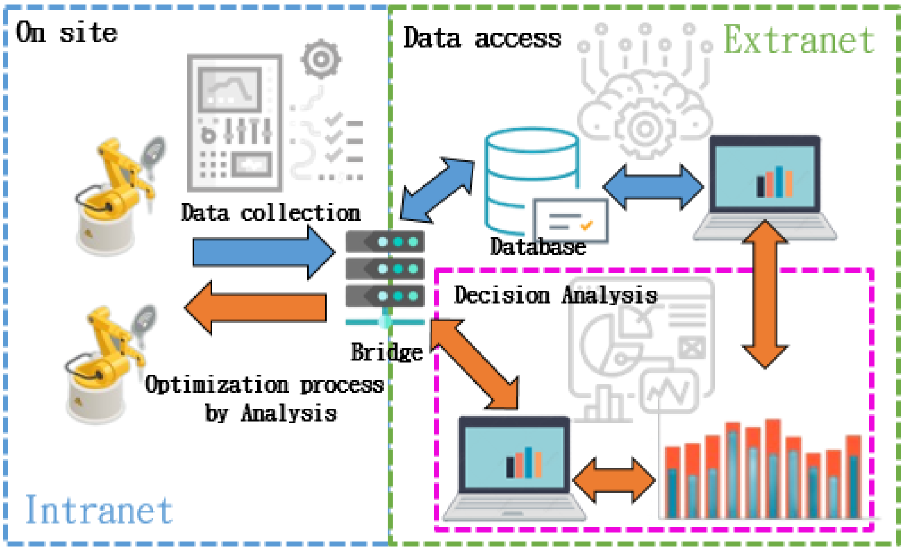

Fig. 7. Data analysis and decision support flow chart.

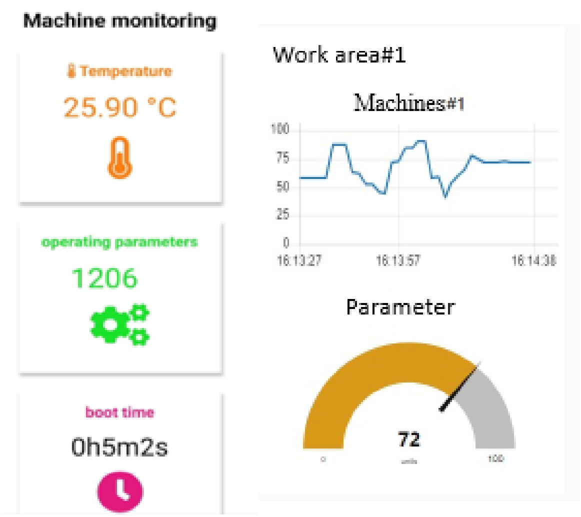

Fig. 8. On-site machine data and visualization interface.

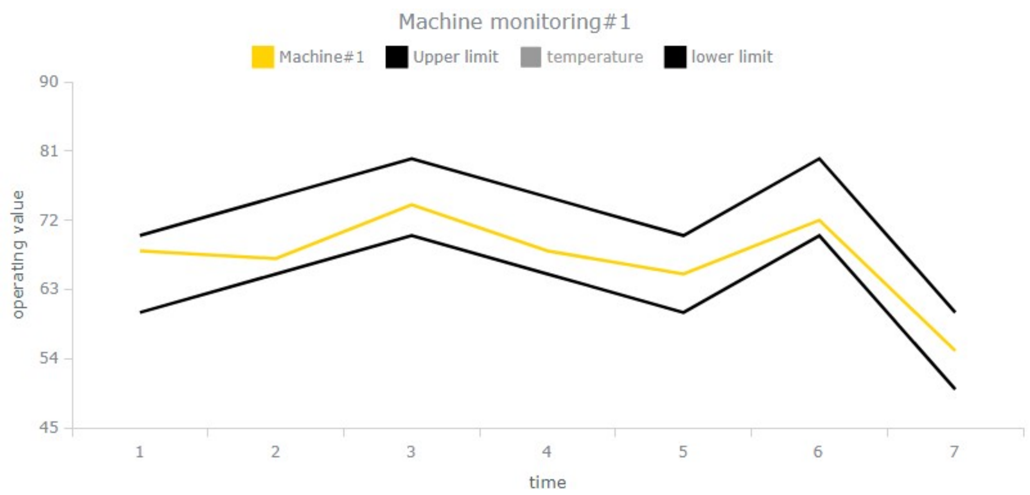

Fig. 9. Prediction of upper and lower bounds for machine.

3.4. Immediate Broadcast of Emergencies

The proposed system employed a real-time proactive push-casting feature for transmitted emergencies via the MQTT protocol (Fig. 10). When a device node detected an exception, the proposed system sent the exception message to the MQTT server through the custom network architecture, and then the MQTT server actively pushed notifications to the mobile devices of relevant managers or employees. This notification mechanism activated the mobile device to draw attention by sound and vibration and sent out alarms until the condition was recovered (Fig. 11). For example, when a machine failed or exceeded the preset range, the system immediately pushed out an alert to the relevant management personnel through the mobile device. A warning light was illuminated on the on-site machine to enhance the visibility of the alarm (Fig. 12).

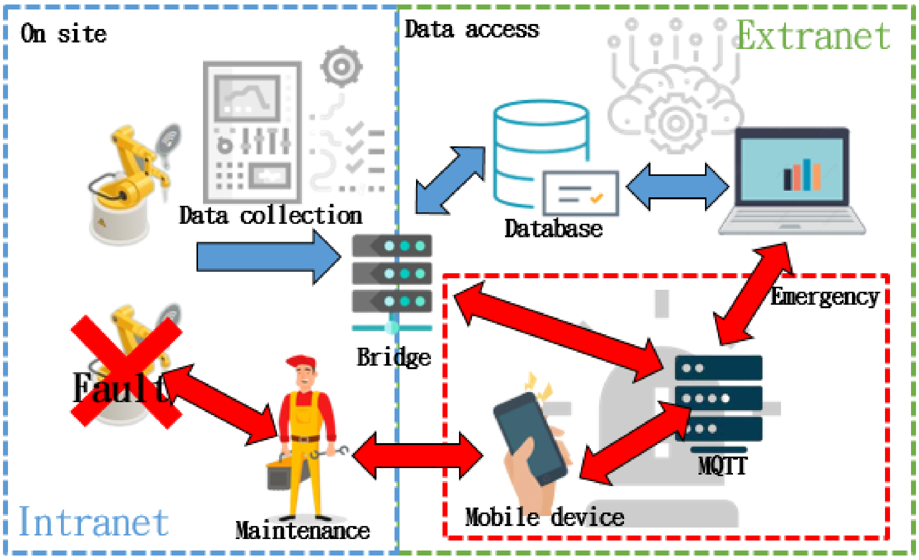

Fig. 10. Emergency push notification flowchart.

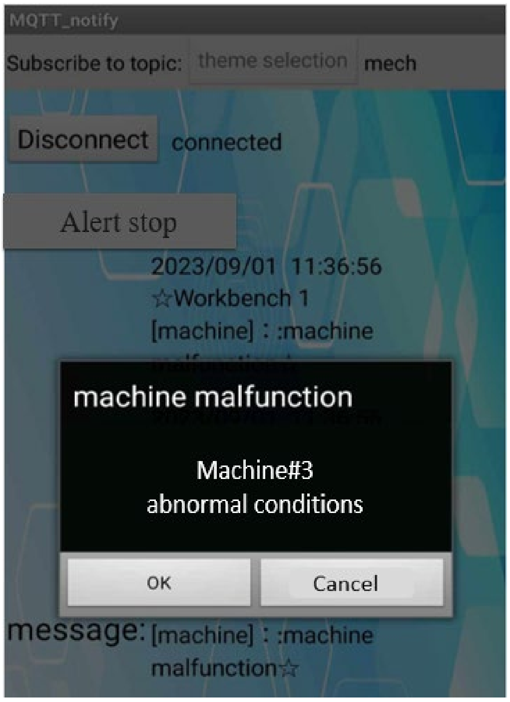

Fig. 11. Screenshot of push notification.

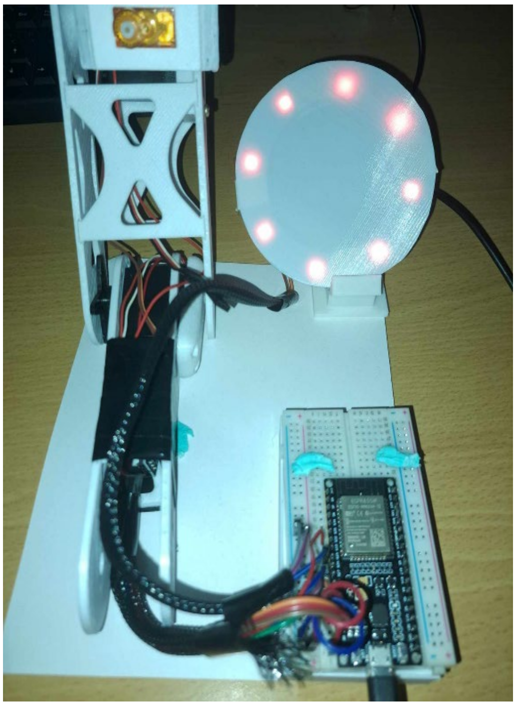

Fig. 12. Warning light was illuminated when emergency.

4. Conclusion

Currently, traditional manufacturing is facing two major challenges: the limited effective response by manual processing and the continued escalation of environmental pressure. These two factors forced the manufacturing industry to rethink and adapt production methods for sustainable operations. To achieve environmental, social, and corporate governance (ESG) goals, companies must adopt innovative approaches to address these challenges. Thus, we proposed a decision support system based on transparent information to overcome the challenges of transforming traditional factories into smart factories. The system included three core ideas (information transparency, scene management, and decision support) and has constructed four major features (low-power self-healing network, information transparent scene management, data analysis decision support, and immediate emergency broadcast). For the comprehensive transformation of traditional factories into smart factories, the system provided information transparency, scene management, and decision-support solutions to effectively respond to various challenges in factory transformation.

Using low-power self-healing network technology to achieve information transparency, supply chain management became more transparent. This allowed managers to monitor consumables and energy consumption in the factory in real time. Such data helped the production be improved with low energy consumption. In the low-power self-healing network, scene management information was transmitted to the database and client, allowing managers to query the data of the current situation in real-time and make appropriate arrangements. The desired production process was carried out in a short period even if changes to the production process were required. In addition, the system detected anomalies and collected data automatically, improving production efficiency while eliminating the risk of single points of failure. Information transparency and data analysis functions helped solve the problem of opaque and non-real-time information. The system's proactive pushing and alert mechanisms ensured rapid response to emergencies. At the same time, the decision-supported function enabled management to make smarter decisions, thereby improving operational results. Visual suggestion was provided to enhance managers' decision-making. In this study, the system proposed not only solved various challenges in transforming traditional factories into smart factories but also complied with ESG standards, demonstrating the company's commitment to social responsibility and sustainable development.

5. Patents

Chang, C. P., Yin, X. X., Guo, W. J. & Chang, H. W.. (2023). Low-Power Auto-Reorganization Network System. Taiwan Utility Model Patent, M645790, September 1.

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