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Analysis and Application of Energy Management in Industry 4.0 with TRIZ Methodology

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Abstract

The advent of Industry 4.0 takes our understanding of technology to a whole new level. The pursuit of profitability is gradually being replaced by business strategies that focus on comprehensive and sustainable operations. As a consequence, the looming energy crisis has become the center of attention, making smart energy management solutions an indispensable cornerstone of industry transformation. For intelligent factories, in addition to upgrading manufacturing equipment, businesses can improve upon traditional models of energy management by collecting and analyzing big data generated by the equipment. Smart energy management, in sum, is a system that effectively coordinates, monitors, integrates, manages, and predicts the operation of multiple sets of equipment, creating a customized energy management platform for every business based on data analytics. The present study is a case study on the facility management system adopted by semiconductor manufacturers. The author discusses the developmental trends in smart energy management within the context of Industry 4.0 based on "failure modes and effects analysis (FMEA)" and the "theory of inventive problem solving (TRIZ)." Building on the results, the author summarizes the potential technologies that meet practical needs and the development of intelligent electrical components that address potential failure modes. Finally, through the application of Internet of Things (IoT) and big data collection and transmission, businesses can conduct predictive maintenance on their in-service equipment to prevent system downtime, realizing the true benefits of intelligent management. The author hopes that the findings of this study can offer useful insights for relevant industries seeking to transform their businesses intelligently.

Keywords: Industry 4.0, TRIZ, FMEA, IoT, Big Data

1. Introduction

With the advances in sensor technology and the increasing penetration of Internet of Things (IoT) devices, the integration of communication and sensor technology has become the key driver for the manufacturing industry's foray into smart manufacturing. Taiwan has transformed its early labor-intensive processing industry into the capital- and technology-intensive OEM industry of today. With the rapid changes in market dynamics, the industry's long-standing advantage is now threatened by other Asian countries, causing a slowdown in the industry's growth. To venture into smart manufacturing, the Taiwanese manufacturing industry needs to transform itself through changes in its manufacturing environment and capacity, along with development in energy and resource allocation. To counter the competitive pressure and changes in external environment, the industry needs predictive analytics skills to improve its operational efficiency and competitive advantage in manufacturing, marketing, and information technology.

Thriving industrial development drove the high emission of greenhouse gas and intensified the energy crisis. Operational objectives for businesses has begun to turn from past emphasis on profit and growth to comprehensive sustainable development strategies. The manufacturing industry implemented reactive maintenance in the past but has moved towards predictive maintenance in recent years, analyzing the large amount of data generated in the manufacturing process to make further predictions; smart energy management is also enhanced to achieve effective energy distribution, low energy consumption, and equipment efficiency optimization. For example, through the implementation of built-in power monitoring sensors in transformers, power system monitoring can detect network abnormalities and perform instant shutdown of equipment affected by tripped circuit breaker, power outage, or electrical issues. Few studies have focused on the practical application of power monitoring equipment in smart manufacturing, which can boost industrial transformation and gives the industry a competitive edge.

This study is focused on the developmental history and significance of Taiwan's industrial transformation from processing to OEM and its future developmental trend in smart manufacturing. Boosted by the integration of IoT, big data analytics, and smart energy management, the industry shall venture into smart manufacturing. TRIZ-based empirical analysis of smart energy management shall be based on smart power monitoring equipment to accomplish an improvement in manufacturing efficiency via preventive maintenance; the Internet's role in factory management system is further discussed.

2. Literature

Taiwan transitioned from an early agricultural society to a fast-growing light industrial society in the 1960s, producing electronic, textile, and plastic products. Taiwan further started development of strategic high-tech industries in the 1980s to accelerate industry upgrade and ride the wave of global industrialization. Despite the fact that recent development in smart manufacturing has outpaced the past growth of industrial automation, the years of accumulated experience in industrial transition and explosive growth in knowledge gained over the past 20 years allow the industry to draw on past experiences for an expedited way to determine solutions. By establishing a problem-solving approach towards management, technology, or operations on the wisdoms of our predecessors, we are no longer bound by existing framework of thinking and can identify the root of our problems via innovative theories, thus leading the technological development of Industry 4.0 and smart manufacturing.

2.1 History and significance of Taiwan's industrial development

The early economic development of Taiwan is built upon its agriculture and light industry. Boosted by the government's Ten Major Construction Projects and its support in key industries, Taiwan accelerated its industrial transformation and improved its competitiveness, gradually developing into a small capitalist economy that draws investment through small and medium-sized businesses. The Taiwanese economy has continued its steady growth in various aspects. The manufacturing industry accounts for the largest percentage in Taiwan's GDP. Among them, the telecommunication and high-tech manufacturing sectors started with traditional computers and video game consoles and moved on to the rapidly-developing laptop market. This, coupled with the rapid development of the venture capital market, established Taiwan as a global hub for semiconductor foundry, packaging/testing, and system engineering, while laying the solid foundation for the optoelectronic industry of solar panel and display panel.

(1) Innovative industrial significance - smile curve

The government encourages new forms of technological R&D and international trade opportunities to stimulate demand and raise awareness for industrial transformation among the domestic manufacturing industry. New ideals and values are therefore the cornerstone for brand development. Market demand and innovative thinking are two concepts of the infrastructure industry, the former concerns the customized demand of clients (patent, technology) and the latter is about ideals and beliefs in the managerial aspect (brand, service). This model corresponds with the smiling curve theory proposed by Acer Group founder Stan Shih in 1992, which divides the industry value chain into three parts: patent & technology, manufacturing, and brand & service. The curve represents value-added, which is low in the middle part and high on the two ends. This theory suggests that for a business to increase its profit, it has to reorient itself into the two ends instead of continuing development in manufacturing. For innovative R&D thinking, one must first find the corresponding market demand through which innovative value can be identified, and a continuous implementation of innovative thinking can be carried out. This is expected to create value through technological innovations of information evolution.

(2) The innovative management model of the high-tech industry in Taiwan

Open innovation is a new form of operational model that has been drawing large attention. The term "open" refers to the model's contrast with past models, which focused on internal innovations without considering external situations. In a closed innovation model, enterprises can only profit through innovations by hiring the best employees and technicians. The open innovation theory facilitates flows across enterprise boundaries for existing internal technologies of an enterprise and external technologies relatively unrelated to the enterprise's business operations (see Fig.1). For example, at the Taiwan Semiconductor Manufacturing Company (TSMC), designers can utilize the open innovation platform to integrate the relationship between upstream IC design clients, IP core partners, and the semiconductor design ecosystem and create a whole new business model for the semiconductor industry. This can help shorten the design-to-manufacture time of products and connect the company's core competitive advantages in technology, manufacturing, and clients (see Fig.2).

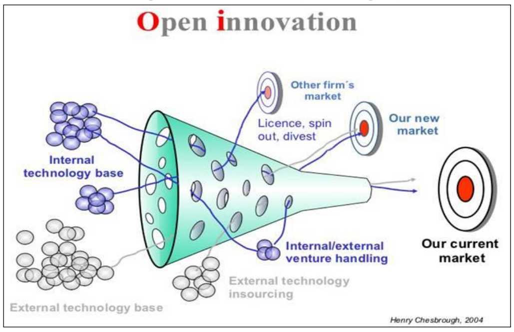

Fig.1 Open innovation
Source: (Henry Chesbrough, 2006)

In recent years, TSMC has been focused on the business opportunities of IoT and wearable technology. The company implemented an ultra-low power consumption technology platform and created a comprehensive design ecosystem that combines mobile communication chips and semiconductor manufacturing with vendors of computing/sensing equipment and communication technology, so as to support the IoT applications of ultra-low power consumption technology. When designing a new manufacturing process for advanced technology, chip designers can utilize TSMC's IP core database for low power consumption technology to improve the success rate of design and manufacturing. Additionally, TSMC also provides various related applications on the technology platform, which can facilitate the R&D of competitive products and shorten time to market. This open innovation platform is expected to bring about another wave of technological growth at TSMC.

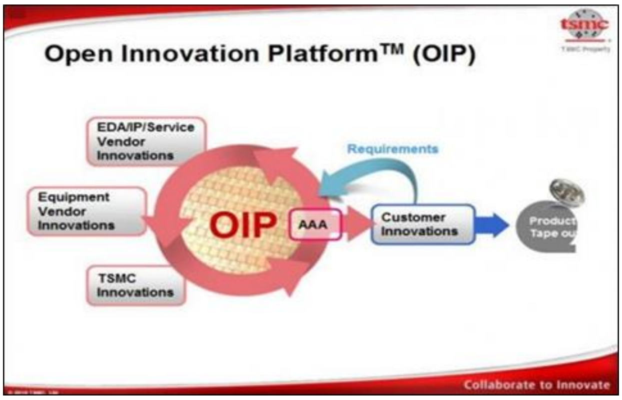

Fig.2 TSMC extends open innovation platform
By Daniel Nenni
Source:https://semiwiki.com/semiconductor-manufacturers/tsmc/462-tsmc-extends-open-innovation-platform/

2.2 Applications and development of smart manufacturing

At Hannover Messe 2011, the German government introduced the topic of Industry 4.0. As the global manufacturing industry enters a new era, many governments are actively pursuing the implementation of Industry 4.0 plans to reinvigorate their domestic manufacturing industry, and through this, maintain their competitive edge and global standing. To ride this wave of global industrial development, Taiwan government has planned for the implementation of Productivity 4.0, hoping to drive industries towards the R&D of smart machinery, Internet, big data analytics-based decision-making, logic systems of human-machine collaboration, etc. This new mindset shall improve manufacturing and operations, and help establish Taiwan's industries as major partners in the global smart manufacturing supply chain.

The early manufacturing industry often adopts reactive maintenance; however, in recent years, the industry's mindset has gradually shifted towards predictive maintenance, which analyzes the large amount of data generated in the manufacturing process to make further predictions. Manufacturing decision-making based on the analysis of these predictions can utilize the integration of various smart systems and implement the concept of smart manufacturing in actual applications within smart factories. Smart factories are built on the foundation of IoT-based manufacturing industry, systematically processing information of the manufacturing process through collection of big data and predictive analysis, in turn helping manufacturing processes achieve the goal of smart manufacturing (see Fig. 3).

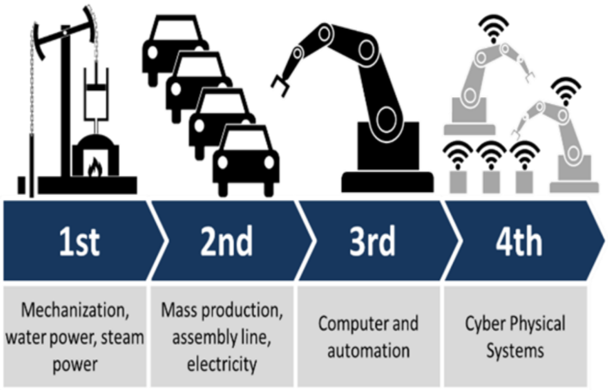

Fig.3 Industrial revolutions and future view by Christoph Roser Source: http://www.allaboutlean.com.

2.2.1 Data utilization in the semiconductor manufacturing industry

With the growing awareness towards Industry 4.0, the global manufacturing industry officially entered the age of big data and IoT, setting in motion the competition in advanced technology manufacturing, with the establishment of smart factories as an item actively pursued by the industry. Smart factories optimize resources to prevent unnecessary waste of resources. Smart transportation reduces the cost of material transportation and improves transportation efficiency. Smart grid technology optimizes power distribution and reduces power transmission loss. Smart products are realized through meeting the low-quantity, high-variety production needs for customized manufacturing, which is achieved by connecting IoT with manufacturing equipment. Smart logistics employs transparent logistics information and real-time monitoring to enhance logistics efficiency and help businesses resolve their own issues. In conclusion, smart factories can perform real-time diagnostics and monitoring on manufacturing processes via IoT applications and the collection and analysis of big data. This can help businesses resolve their own issues, effectively improving yield and enhancing the integration of production control (Kagermann, H., Helbig, J., Hellinger, A., & Wahlster, W., 2013).

In addition to the robust foundation upon which the development of the Taiwanese manufacturing industry was built, the industry also possesses advantages in the flexibility of supply chain cooperation and its experiences in manufacturing management. For example, the semiconductor manufacturing industry consists of upstream IC design companies, midstream IC manufacturers, which design and manufacture semi-finished goods. Semi-finished goods are then diced, packaged, and tested by the downstream companies before being sold to system vendors to produce system products. The comprehensive industrial cluster and professional division of labor have helped Taiwan stay ahead in the global competition of semiconductor manufacturers. How do we maintain this advantage in advanced technology? Smart manufacturing is probably the best answer to that question. Real-time decision-making is the heart of smart manufacturing, which is achieved through the integration of equipment engineering capability, manufacturing execution systems, manufacturing equipment, and automated material handling system.

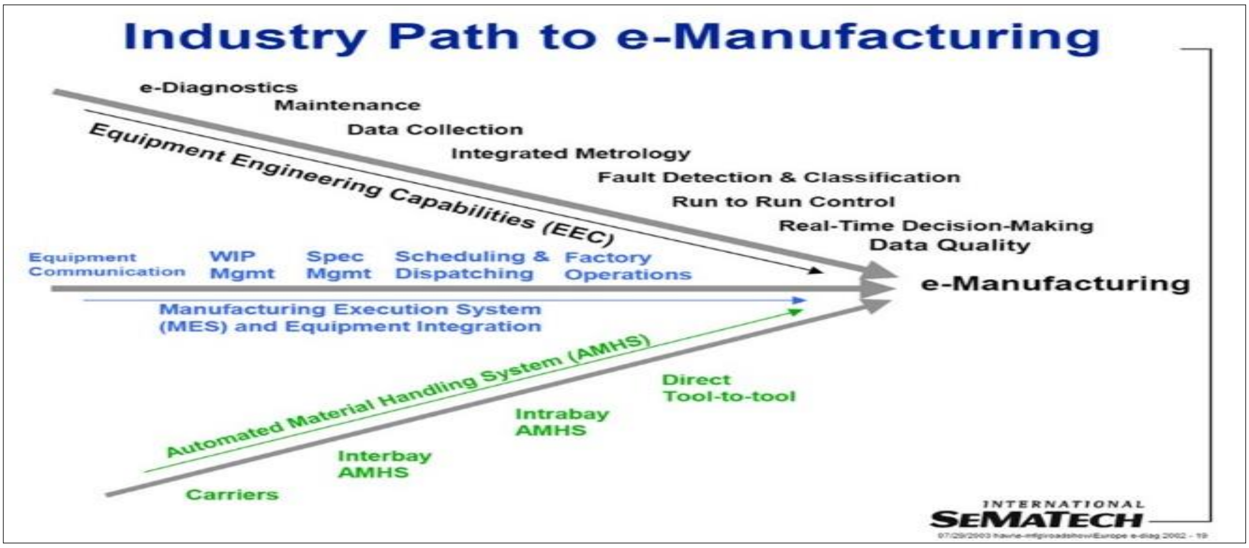

Fig.4 Electronics manufacturing roadmap
Source: International SEMATECH e-Diagnostics and EEC Guidance 2003

Equipment engineering capability is smart decision-making involving error prediction/classification and run-to-run control system. These are implemented through electronic diagnostic technology and integrated measurement via the collation and analysis of data concerning the equipment, personnel, process, and information of a manufacturing process (see Fig.4). The integration of manufacturing execution systems and manufacturing equipment includes communication between equipment and the management of manufactured goods and their specifications, which can facilitate factory operations and help with operational scheduling. This improves the flexibility of manufacturing systems and shortens reaction time. Automated material handling systems can further increase the flexibility and efficiency of transportation via the management of factory transportation carriers and the automated material handling system and direct transportation between and within areas.

2.2.2 IoT applications—increasing capacity and improving yield

In order for enterprises to strike a balance between cost and quality, the improvement of yield has become an important issue in production control. If an effective improvement of yield cannot be achieved, it can incur risks of under-supply or late delivery; business reputation is therefore an important criterion in choosing companies in the supply chain. With the globalization in supply chains, international collaboration and co-design have become major trends in the current high-tech industry. Increasing capacity and improving yield through the interconnection between system technologies are therefore important parts of advanced technology manufacturing and also a major element of trust in international enterprises. By implementing the idea of smart manufacturing, we shall observe a clear effect the Internet has on manufacturing. Through a mutual understanding of manufacturing equipment status and operational scheduling between enterprises, prompt reactions and general inventory management can be carried out between systems. Between the accelerated manufacturing and the reduction in manual inventory control, businesses can also reduce production defects. Enterprises should easily see quick results and increased profit after implementing smart manufacturing. In the long term, enterprises can also see a boost in corporate image and business reputation.

2.2.3 Smart energy management

Based on past experiences, equipment efficiency improvement and operational optimization can reduce energy consumption by 20 to 30 percent. In recent years, several enterprises have come under increasing pressure for energy conservation and carbon reduction from government policies, supply chains, and corporate social responsibility. The sound utilization of smart energy management technologies to achieve the virtuous cycle of effective energy distribution, low energy consumption, and equipment efficiency improvement is therefore an important objective sought by enterprises. The Industrial Technology Research Institute’s Industrial, Science and Technology International Strategy Center defined the field of smart energy applications: power system monitoring (infrastructure end; power generation, transmission, conversion, and distribution systems) and environmental energy conservation/comfort level detection (user end; smart meter, smart plug, thermostat, smart gateway, smart lighting, smart smoke detector, smart home appliance, etc.). The most important technology that constitutes the components of all major application systems is a sensing technology capable of detecting environmental energy conditions at all times.

The core concept of power system monitoring is the use of electrical sensors placed throughout smart energy systems and power transmission, conversion, distribution, and consumption systems to issue timely warnings for detected electric power system anomalies and establish bi-directional interaction between electric utility companies (power distribution) and end-users (smart energy consumption). This can reduce electrical load and improve power consumption efficiency, so as to reach supply-demand equilibrium in electric power. For example, a supervisory control and data acquisition (SCADA) system is an actual application of an automated electrical distribution system on the power distribution/transmission end. A SCADA system monitors electrical anomalies in electrical network equipment via various built-in power monitoring sensors (current sensors, capacitive/inductive liquid level sensors, phase detectors, etc.) in transformers, so as to perform instant shutdown of equipment affected by tripped circuit breaker, power outage, or electrical issues.

3. Materials and methods

This study is a case study of a semiconductor manufacturer and is primarily centered around the process chilled water system on the fabrication end. An observation and analysis of the development and data collation of smart electric power sensor technology are performed by first describing the issues in system technologies, followed by a discussion of technical contradictions and using the inventive principles presented by the contradiction matrix to find the best technological application for sensor components. Finally, Failure Mode and Effects Analysis (FMEA) is utilized to analyze the process chilled water system for improvements in smart energy management, so as to improve efficiency and implement predictive maintenance. This chapter contains two sections, the first explains the problem-solving process of TRIZ, followed by a discussion of FMEA.

3.1 TRIZ

TRIZ is a tool of inventive problem-solving developed by Russian mechanical engineer Genrich Altshuller by analyzing hundreds of thousands of global patent literature and summarizing their problems and solutions. Beginning in 1946, he found systemic patterns behind the thinking and behavior of successful, innovative inventors. In the development of this generalized problem-solving process methodology (see Fig.5), Altshuller clearly defined 39 basic engineering parameters and 40 inventive principles to solve contradictions between any two of the 39 parameters; the inventive principles are used for problem-solving, turning abstract principles into concrete solutions. The development of the TRIZ theory by Altshuller and his research team via a cross-disciplinary integration of principles and rules summarized the various regular patterns followed by technological development and evolution, and solved all kinds of technical and physical contradictions through innovative principles and rules.

Further investigation into the applications of the 40 inventive principles of TRIZ shows that within the concept of Industry 4.0, systemic improvement or changes can be approached through systematic thinking and system life cycle can be determined through equipment and internal components. This study classified the inventive principles into three categories: conceptual principles, technical principles, and material principles. The 40 inventive principles and their classification have a multi-faceted way (e.g., weight, shape, transmission mode, etc.) in approaching actual applications or design processes. By using the aforementioned classification, we can turn abstract problems into concrete ones and hope to find the best solutions for future designs that simultaneously solve systemic problems and improve operational efficiency.

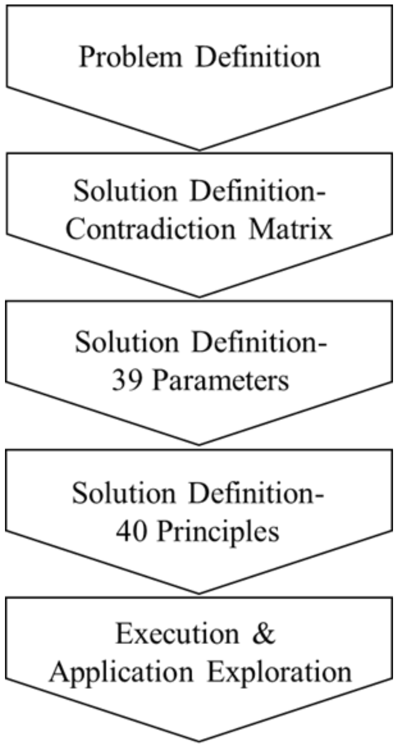

Fig.5 The problem solving process of TRIZ

3.2 Failure mode and effects analysis (FMEA)

FMEA is a design tool based on past experiences and failures. It can continuously verify and improve operating procedures in design, R&D, manufacturing, and assembly by performing careful analysis at the designing stage, detecting and eliminating factors of negative effects such as poor designs and human errors, leading to the goal of overall system optimization.

The FMEA methodology primarily uses system function reliability block diagrams and analysis tables to list potential failure modes of systems, products, or manufacturing processes. The occurrence of failures can be prevented by analyzing causes and potential effects, assessing priority for improvements, and drawing up effective improvement plans. After a formal implementation of FMEA into system analysis, the failures' effects on systems are evaluated. We can use the Risk Priority Number (RPN) to assess the risks and implement improvements based on the assessed priority. To calculate the RPN, we need to first evaluate the following:

(1) Severity:

The impacts on systems or personnel after the occurrence of the failure mode. This is evaluated based on the actual degree of the effects.

(2) Occurrence:

The likelihood of the failure mode occurring. This is usually determined based on the average number of occurrences in a fixed time period.

(3) Detection:

The likelihood of the detection of the failure cause in systems or manufacturing processes.

McDermott et al. put the factors of severity, occurrence, and detection on a scale ranging from 1 to 10 and defined the significance of each level of rating. However, due to the many restrictions imposed by practical considerations, the calculation of risk priority number (RPN) is: RPN = Severity (S) × Occurrence (O) × Detection (D).

4. Empirical analysis

Information integration on a smart energy management platform is highly correlated with the data monitoring of all systems. After diagnosing equipment status via data analytics, we can plan for the basis of predictive maintenance, thus reducing unnecessary hidden costs in manufacturing. In said platform, IoT is used for a customized energy management system that integrates technology based on end-to-end data collation. After technology integration, the system possesses the smart management capabilities of failure prediction, power management, auto-balancing control, and automated operation scheduling. Although this concept has already been implemented in the development of smart factories, energy management requires further improvement in equipment efficiency and data optimization. We hope to propose operational plans for overall efficiency enhancement in accordance with management decision-making in the future.

The subject of this case study is the process chilled water system of the semiconductor manufacturing industry; this system is provided for the manufacturing process and air conditioning operations. As seen in Fig. 6, the main water chiller unit has a higher energy consumption compared to the rest of the chilling equipment. The benefits of predictive maintenance can therefore be achieved by finding the operational energy consumption of the equipment in the system. After combining energy management principles with the analysis of smart electrical sensors using TRIZ and analyzing big data through the IoT transmission framework, we combine the result with the equipment characteristic curve and transmit it to the smart energy management platform for application analysis. This allows the platform to automatically convert energy consumption and have the operations set at the optimum energy-saving control point, thus achieving the goal of improved efficiency and predictive maintenance. The implementation of smart energy management platform can increase the industry's global competitiveness by combining innovative technologies with the energy management system of the existing Facility Monitor and Control System (FMCS), utilizing FMEA to reduce system risk, and planning for predictive management.

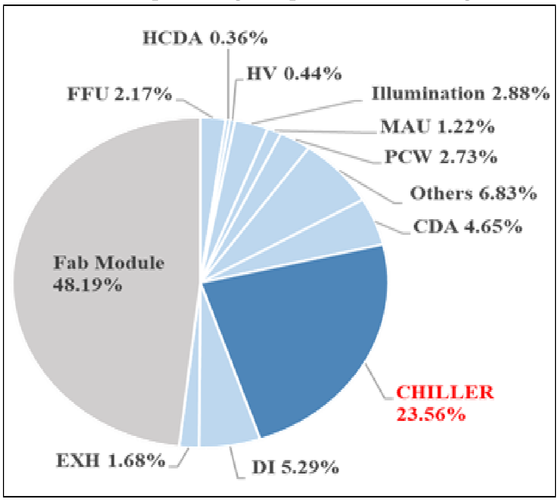

Fig.6 The proportion of electric power systems

4.1 Applications of process chilled water system

This is a process chilled water system of the semiconductor industry. Its function is to provide for the manufacturing process and air conditioning operations. As the main water chiller unit has a higher energy consumption, energy consumption data of the system is determined and transmitted via IoT to the smart energy management platform for further application analysis, so as to achieve the goal of improving efficiency and predictive maintenance. A process chilling system has a higher percentage in power consumption and consists of various smaller units, including power supply systems, control elements, and operational support equipment. Current measures employed are mostly regular maintenance, preventive maintenance, or predictive management. This section is a discussion of the use of smart electronic sensors and TRIZ problem-solving theory for innovative inventions, and the preventive evaluation and analysis of components capable of energy management.

(1) Operational equipment: Pumps

The pumps within a process chilling system are critical to its operation. Equipment overload damage (see Fig.7) caused by abnormal voltage, environmental issues, or poor insulation can lead to system shutdown if the components are not given preventive replacement/maintenance. Determination of equipment status is achieved by measuring the relevant voltage and current and performing predictive failure evaluation based on the regular maintenance cycle or component life cycle. However, technical difficulties concerning the actual use of certain components should be noted in advance.

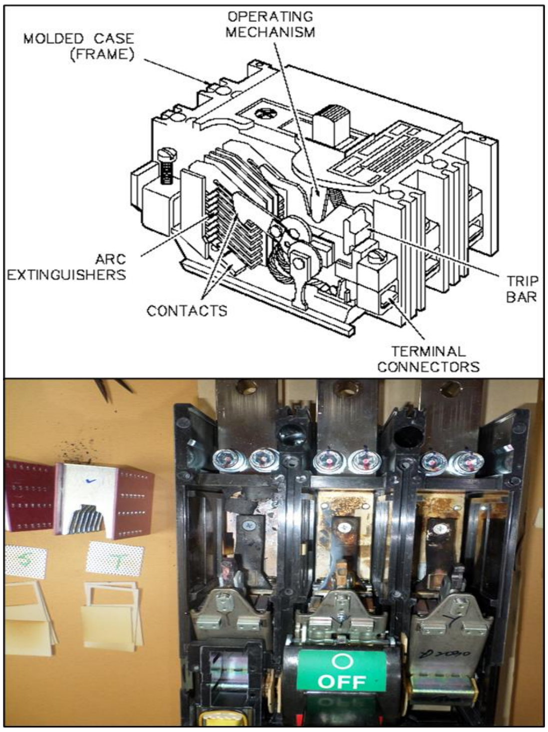

Fig.7 Abnormal pump equipment

(2) Control system: Electrical equipment switches

No-fuse breakers (NFBs) are the first line of preventive measures in all systems. The purpose of such breakers is to provide systems with overcurrent protection, overload protection, and short circuit protection. When in use, degradation of internal components is not easy to spot (see Fig. 8), which can lead to the breaker failing to cut power or trip in case of anomalies, which may in turn cause downstream equipment damage or fire, threatening personnel safety. Under regular safety standards, NFBs undergo service life evaluation; and the service life of internal mechanical and electronic components are positively correlated. Currently, preventive maintenance and replacement can only be performed on equipment with anomalies in energy use by using infrared thermal imaging to measure the thermal radiation generated by components.

(3) Control system: Multi-function power meter

The semiconductor manufacturing industry has a complicated model in power supply and demand. For major energy consumers in the industry, effective energy management can only be achieved by controlling manufacturing or operational power consumption. Digital panel meters are used to measure the voltage, current, power, frequency, and demand of a power circuit, and are therefore important equipment in industrial energy management. The regular data transmission mode establishes physical wiring layouts and completes data output via RS-485 standard serial communication protocol, achieving anomaly detection and management on the remote monitoring platform. However, effective energy control cannot be achieved if the transmission fails due to issues with the physical wiring (see Fig. 9), if there are power detection issues, or if the meter has internal component damage. Using the TRIZ problem-solving theory for innovative inventions, we can move towards the development of meters or related sensors that utilize wireless communication technology, so as to implement improvements in areas where physical wiring are difficult to place or in meters with power anomalies.

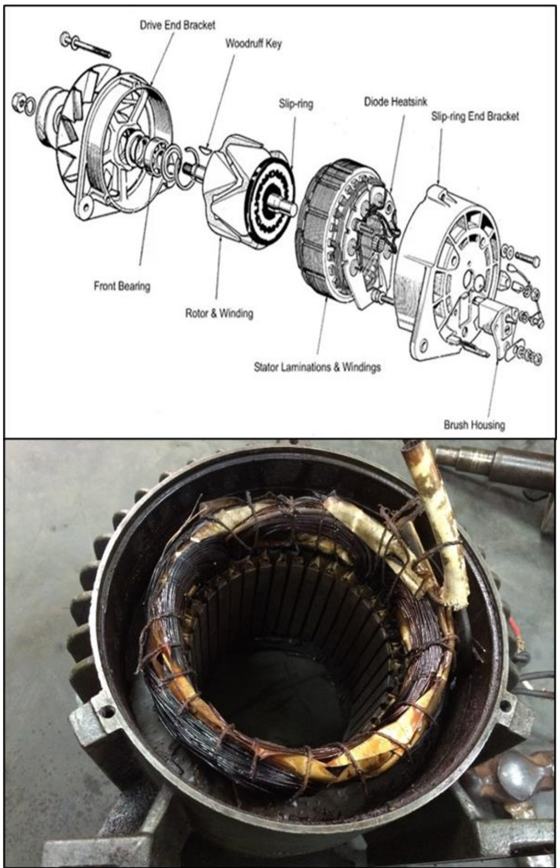

Fig.8 Abnormal switch equipment

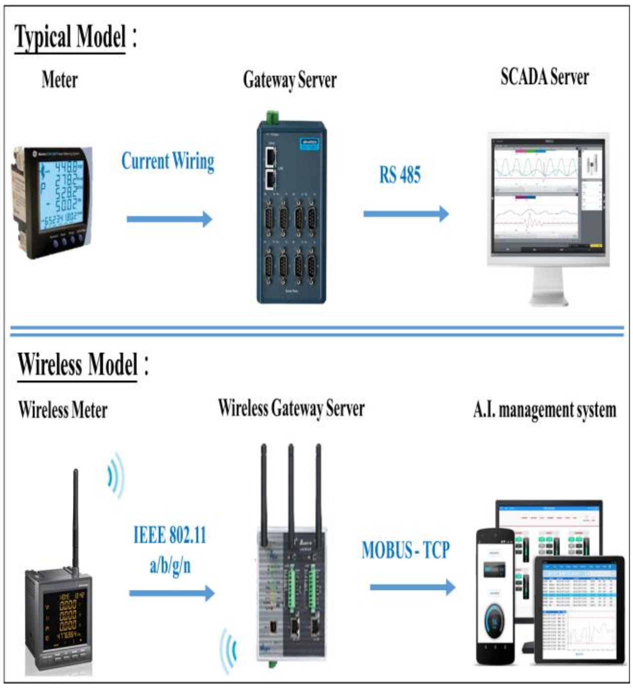

Fig.9 Energy management and wireless data transmission

(4) Uninterruptible power supply (UPS)

The primary function of a UPS is to provide the load with the stored energy in its battery when it detects voltage anomaly or power outage in the mains (Taipower), providing an uninterruptible power supply until power returns. Various control elements in the process chilling system require uninterruptible power in order to power the operations of control elements during system anomalies. UPS operates in standby mode over long periods of time and therefore require better ventilation to control the temperature for its internal power conversion and energy storage units. The internal fans are controlled via signals based on the monitored temperature; overheating inside equipment can lead to degradation of electronic components (see Fig. 10). The operational status of the fans is currently determined through system maintenance/replacement or through the experience of inspection-performing personnel. Using the TRIZ problem-solving theory for innovative inventions, we can develop sensors capable of monitoring the operational status of fans, collating their data, and performing predictive failure evaluation before any occurrence of fan failure or other anomalies. An equipment health inspection system is established on the smart energy management platform to perform decision-making for failure prediction and diagnosis.

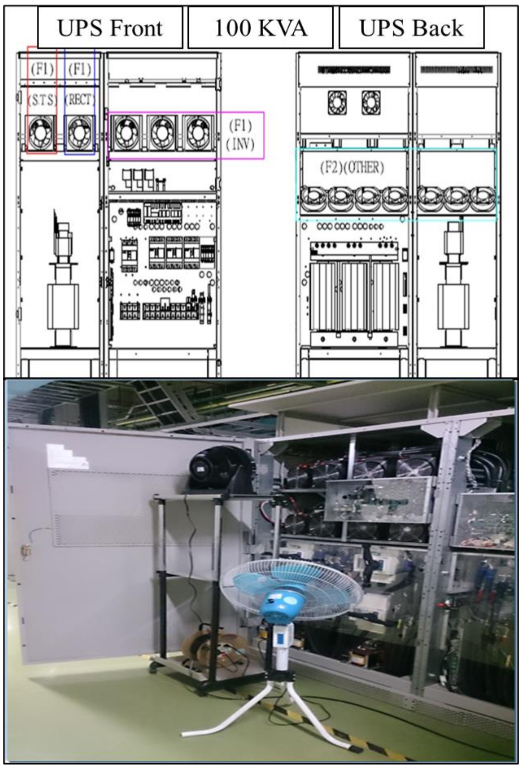

Fig.10 Abnormal UPS equipment

4.2 TRIZ analysis of the technological development in smart electrical sensors

In this age of rapid technological development, stable power supply and electrical accident prevention are vital to production control. The development of related smart sensors and the establishment of smart grids ensure equilibrium in power distribution, which is the basis for government implementation of energy management and data collation; it is also an energy policy objective for many countries around the world. Applications of smart grids and related sensing technologies entail the implementation of said technologies in manufacturing processes or electrical equipment. By integration the electrical sensors in various electrical equipment and integrating them with the remote power monitoring system, we can detect overload or equipment anomalies in the overall system. In the case of anomalies, the remote monitoring system can transmit control signals to control equipment operation, which in turn ensures operational safety, prevents accidents, and achieves energy control.

4.2.1 Description of system technical problems

(1) Miniaturized electronic design

In this age of smart energy grid development, stable power supply and safety need to be major considerations for overall systems. For this reason, suitable current transformers should be used to measure electric current. A traditional current transformer (TCT) operates by measuring the current in the primary winding induced by the flux generated in the internal iron core. In the case of electrical system failure, instantaneous non-linear current can occur with a power surge, which threatens the safety of the electrical system. Due to their large size, TCTs can affect the planning of manufacturing facilities and their layouts, and require time and labor costs for their regular maintenance. Therefore, improving on the size of TCTs is the primary goal (see Fig. 11) in practical application. However, the size reduction in current transformers will affect their precision, resulting in various issues, including error when performing measurement on components.

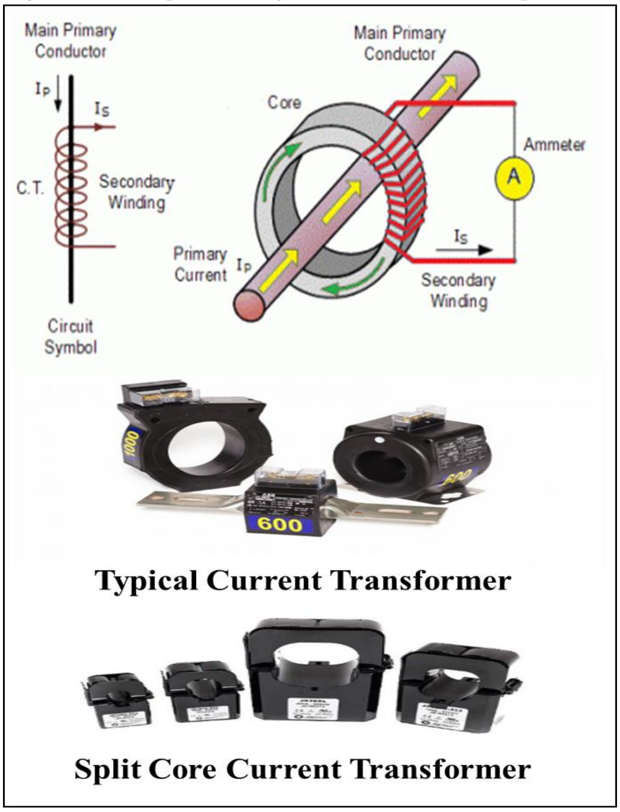

Fig.11 Current transformer technical principle

(2) Wireless inductive charging

A power supply is another point of consideration for improvements on smart sensors with wireless transmission capability. Current sensors placed in power grids require the design of power supply in accordance with their needs using the TRIZ theory for innovative thinking. The design of a wireless charging power source is present in many inventions; the convenience and safety of its primary design make it suitable for applying the TRIZ problem-solving theory for innovative inventions (see Fig.12). By combining wireless charging with current sensors, we can create smarter sensors.

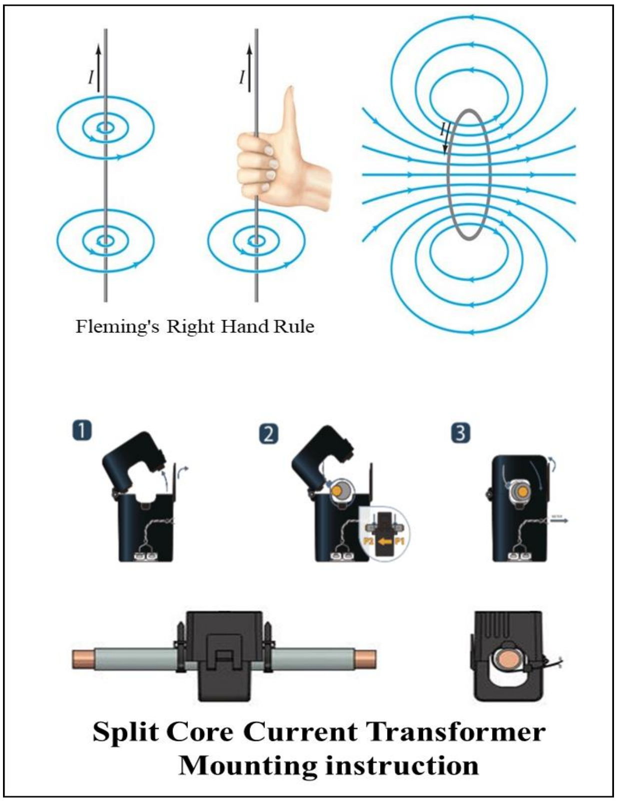

Fig.12 Magnetic field technical principle

4.2.2 Applications of TRIZ contradiction matrix

(1) Miniaturized electronic design

- Improving technical parameter: 12. Shape

"Shape" is the functionally necessary internal and external shape/contour of systems and its elements. For the semiconductor manufacturing industry, which seeks high quality and yield, the process planning, regular maintenance, and breakdown maintenance of manufacturing facilities are heavily considered when designing their layouts. Small-dimension designs free up more space and allow flexible planning in assembly lines. Improvements in time and efficiency can also be seen in the installation, transportation, replacement, and maintenance of equipment.

- Worsening technical parameter: 28. Measurement accuracy

"Measurement accuracy" is the level of deviation or error in measurement—i.e., the closeness of the measured value to the actual value. The electronic design of system components can improve data transmission capability and effectively improve the accuracy and stability of measured data. Miniaturized design enhances safety in installation and operation.

The technical parameters 12 and 28 correspond to principles 28, 32, and 1 of the forty inventive principles presented in the contradiction matrix. By using Principle

28: mechanics substitution—use electric, magnetic and electromagnetic fields to interact with the object—we acquired the result. As electronic components continue the trend of thin, light, and miniaturized design, corrective analysis is performed on the fundamental electrical and mechanical structure and mechanical components, so as to improve their shapes and plan for integrated design and optimizing measurement accuracy, thus achieving the goal of miniaturized electronic design. In addition to size and measurement accuracy issues, the analysis of wire charging applications in TCTs is as follows:

(2) Wireless inductive charging

- Improving technical parameter: 38. Extent of automation

The technical parameter "Extent of automation" is the extent to which a system or object performs its functions without human interface. Based on the changes in data management and operation mode, energy consumption can be reduced in peripheral devices by reducing electronic sensors or putting them on standby.

- Worsening technical parameter: 23. Loss of substance

The technical parameter "Loss of substance" is the partial or complete loss/waste incurred on a system. Energy consumption of data transmission often uses external power supply as the main power source. The long-term continuous operations of the system can shorten component service life. Additionally, the greater the power dissipation, the greater the power demand.

The technical parameters 38 and 23 correspond to principles 35, 10, and 18 of the forty inventive principles presented in the contradiction matrix. By using Principle 18: mechanical vibration—using an object's resonant frequency or using combined ultrasonic and electromagnetic field oscillations—we acquired the result. The accompanying planning for component power supply is another developmental focus of miniaturized electronic component designs. As the original plan for power supply may require revamp, energy allocation and demand are technical hurdles that need to be overcome. Through the combination of miniaturized electronic design and electromagnetic energy exchange, wireless charging technology can deliver electrical energy to smart electrical sensors via magnetic induction or resonance, achieving the goal of improving wireless power technology applications.

4.3 TRIZ analysis of the data collation in smart electrical sensors

The communication framework of smart manufacturing plants achieves the goal of smart management by enhancing control over the communication equipment, network environment, and cloud management of automation equipment. Through the use of IoT real-time detection capability, long-term monitoring, and regular inspection of equipment status, the framework can report anomalies when the equipment exceeds the alarm threshold value. This gives management control over equipment power and environmental variables via the energy management system. The implementation of IoT in energy management provides manufacturing processes with an advantage. As there is a diverse range of electrical equipment in manufacturing plants, anomalies could only be detected through regular inspection and maintenance. In order to provide management with the capabilities of remote management, monitoring & diagnostics, and energy consumption awareness, IoT-connected wireless sensors are combined with cloud data application (see Fig.13). This is critical to the management model of smart factory applications.

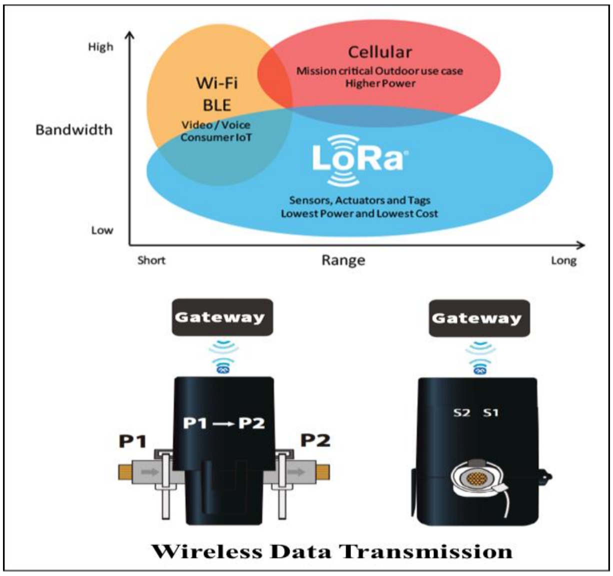

Fig.13 Range vs. bandwidth for IoT connectivity technologies

4.3.1 Description of system technical problems

(1) Cloud data collation—wireless transmission system

In the communication framework of a traditional manufacturing plant, electrical equipment, detection functionality, and related sensor applications all rely on wired communication. However, the number of sensors installed has increased with the growing demand for equipment monitoring, resulting in signal interference and connection issues between components, which in turn affect the collation, storage, and immediacy of data. Furthermore, with the increasing number of physical wiring due to the growing demand for connection, these plants now face mounting installation costs incurred by the need for long-distance communication and the shortage of equipment connection points.

4.3.2 Applications of TRIZ contradiction matrix

- Improving technical parameter: 27. Reliability

The technical parameter "Reliability" is a system's ability to perform its intended functions in predictable ways and conditions. Through the use of developed network protocol systems, we separated functionality and applications, turning it into a subnetwork system. This helps alleviate the connectivity issues between different systems and improves the reliability of data collation.

- Worsening technical parameter: 26. Quantity of substance

The technical parameter "Quantity of substance" is the number or amount of a system's materials, substances, parts, locations, or subsystems. Since a large number of network devices can cause signal interference, the initial network framework must be separated into various subnetworks.

The technical parameters 26 and 27 correspond to principles 21, 28, and 40 of the forty inventive principles presented in the contradiction matrix. By using Principle 21: Skipping—enhancing transmission speed and efficiency and shortening transmission time—we acquired the result. The number of equipment sensors is increasing with the implementation of smart manufacturing. Because of the varying development of sensors in different equipment applications, the integration difficulty of physical wirings due to the separation of independent systems, and the lack of reserved spots, the functionalities of wireless transmission technology in the smart management framework are separated, using long-distance communication to perform wireless data collation.

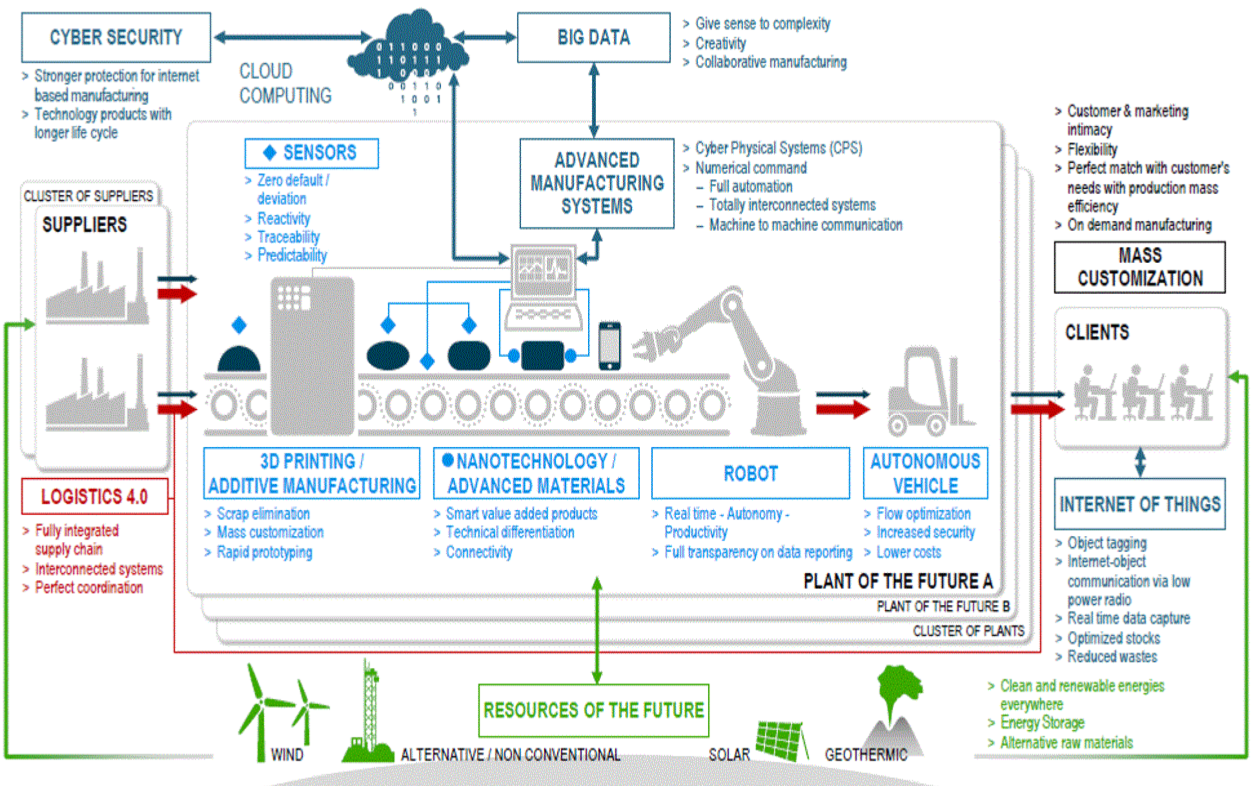

Fig.14 The framework of industry 4.0 ecosystem Source: Berger, R. (2015)

To summarize the preceding analyses, an electronic sensor for electric power has all the functionalities of a traditional electric power sensor. However, besides the differences in operating principle and structure, an electronic sensor for electric power also alleviates issues of dimension, weight, and cost, while fulfilling the demand for high-precision measurement and system protection. The new form of energy transmission technology also improves on certain flaws concerning safety, including the elimination of the need to plug and unplug cables, thus avoiding electrical contact failure. New electric power sensors based on the aforementioned technologies can enhance their sensing capabilities and perform wireless transmission of data.

By using wireless charging to reduce cost, implementing electric power monitoring sensors in energy management, we can establish customized systems that combine energy-saving management and energy safety (see Fig.14). We can also incorporate sensors of different applications to move towards a form of manufacturing that integrates multiple functionalities.

4.4 FMEA evaluation of application and management

The aforementioned FMEA analysis table was used in this study to evaluate whether applied innovative technologies can overcome potential critical failure modes in the system, thus reducing or eliminating their effect on the system. The RPN—calculated from severity, occurrence, and detection—is used to determine the improvement's effect on the system and the level of technological implementation, so as to draw up improvement plans or related control measures (See Table 1). Through the informatization of big data and the implementation of new technologies in the smart energy management platform, we can improve on the existing energy management model and benefit from predictive maintenance.

Table 1. The FMEA process of cooling water

Item	Original RPN	Measures	Improved RPN
Pump	256	1. Review of regular replacement and maintenance of equipment components. 2. Installation of additional smart sensors to measure related data and transmit data to the smart energy management platform via wireless transmission.	32
Electrical equipment switch	144	1. Regular equipment maintenance 2. Evaluate the design for smart sensors to automatically collect related data and transmit data to the smart energy management platform, so as to control load transfer.	48
Digital panel meter	192	Review of equipment's smart functionalities (e.g., wireless transmission), collection of related data, and transmission of data to the smart energy management platform.	48
UPS	320	Plan for the implementation of equipment inspection management functionality, which can determine the equipment life cycle for the smart energy management platform to perform predictive management.	64

We utilized FMEA to analyze the improvement in risk priority numbers (see Fig.15). Traditional energy management generally uses limited unidirectional transmission, which means that data is transmitted to the management platform via internal networks. However, power distribution data can often be difficult to monitor due to various engineering factors such as wiring layout or interference, resulting in losses and making it difficult to establish a suitable energy management policy. In comparison, smart energy management implemented with smart electrical sensors provides effective control of equipment data via IoT, achieving diverse integration and management between management platforms. This highly efficient interaction can facilitate the functionalities of maintenance/expansion and real-time monitoring in the energy management system. Data analysis performed by the smart energy management platform can be further used to development new forms of IoT and sensors, improving efficiency and management.

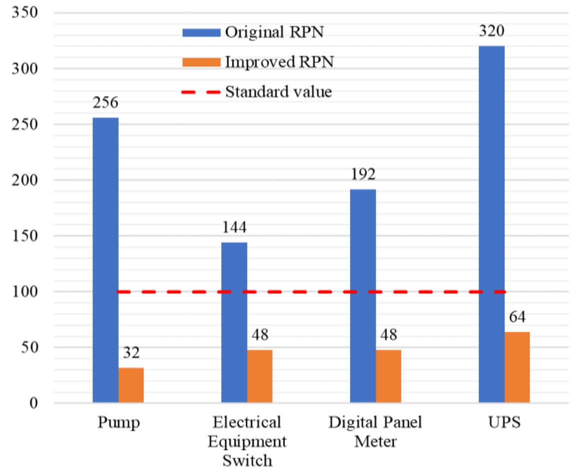

Fig.15 The bar chart of RPN

5. Conclusion

The implementation of Industry 4.0 in enterprises fulfilled the manufacturing model of smart manufacturing systems. This includes smart manufacturing, smart equipment, smart energy management, and smart manufacturing supply management. This study approaches the case study of smart energy management in the semiconductor industry from the data collation aspect. The technological integration of network transmission, data collation, and equipment operational status help businesses determine potential equipment anomalies within an acceptable time period and propose predictive management. This allows for enhanced manufacturing efficiency and flexibility while avoiding late delivery. In conclusion:

(1) Complete optimization of energy efficiency by achieving real-time monitoring and data management via smart equipment

In the past, electrical equipment management generally utilized limited unidirectional transmission, which uses internal networks to transmit electric power data to the management platform. However, power distribution data can often be difficult to monitor due to various engineering factors such as wiring layout or interference, resulting in losses. Through the implementation of smart electric power sensors and customized design in accordance with manufacturing processes, effective data control of equipment can be achieved via IoT. This improves energy efficiency, reduces operational cost, and achieves diverse integration and management between management platforms, greatly benefiting commercial smart energy management strategies.

(2) Complete optimization of manufacturing efficiency by utilizing real-time information integration to achieve predictive management

With the technological breakthrough in sensors, the combination of smart energy management systems and electric power sensors has replaced the management model of the past, which is limited to local monitoring, manual inspection, and incompatible electronic systems. Improvement in the automation model's real-time digital information concerning maintenance management, data collation, predictive maintenance, and environmental monitoring can help determine potential operational risks of equipment, including energy consumption anomalies and risks in predictive maintenance planning. This reduces the risks and losses incurred by failure and shutdown, and can further facilitate bidirectional analysis of other systems and equipment information. Improvement of the overall operational effectiveness of manufacturing processes can be achieved by improving unit inspection system, unifying standard procedures, and progressively establishing database systems, thus achieving the goal of procedure optimization.

(3) Reach optimal operation by helping business resource allocation via advanced smart energy management

In the case of manufacturing process anomalies or product complaints, a reverse data lookup can be performed on the data collected via the smart energy management platform. This allows businesses to conduct analysis over the 5M1E factors (man, machine, material, method, measurement, environment) and implement control measures accordingly, thus improving energy efficiency, reducing operating costs, and implementing green supply chain management.

As the establishment of the smart manufacturing framework completes, corporate departments related to the planning of management shall begin to play bigger roles within the enterprise. With technological advances come improvements in engineering technologies, and management shall also face their corresponding problems, including: (1) Is the new business model introduced for overall operations or management decisions? (2) How to further development in smart manufacturing? (3) Can modular manufacturing systems be implemented? (4) If co-design is required, can alliances be formed with clients, contract service providers, or competitors to enhance each other's technological capacities? Future development of smart applications shall focus on interactive applications combining artificial intelligence and virtual reality. With computational thinking moving from mobile-first to artificial intelligence, smart applications utilizing deep learning has begun to emerge in various high-tech industries. As men become used to living technologies, back-end data analytics and computation are merely the results of deep learning; decision-making, comprehension, and critical thinking are still performed by management. As we ponder over the fast-evolving future of human-computer technologies, the comprehension of the analytic judgment, regulation enforcement, and moral philosophy concerning smart applications is questions that need further discussion on another level.

References

Berger, R. (2015). The digital transformation of industry. Federation of German Industries (BDI), Munich (www.rolandberger.com/publications/publication_pdf/roland_berger_digital_transformation_of_industry_20150315. pdf).

Cheng-Juei Yu. (2014). Instant Insight: Build on STREAMS Real-Time Massive Analysis Power Based on Existing Analysis Tools. *IBM INSIGHT,* November 7, Taipei, Taiwan.

Cheng-Juei Yu, Kuan-Yu Lu, Wei-Wen Wu & Shih-Hsiang Ting. (2016). Towards industry 4.0 - Application examples of big data analysis in manufacturing. *Journal of Electrical Engineering*, 2, 68-77. DOI: 10.6328/CIEE.2016.2.09

Chen-Fu Chien, Kuo-Yi Lin, Jiuh-Biing Sheu & Cheng-Hung Wu. (2016). Retrospect and prospect on operations and management journals in Taiwan: From industry 3.0 to industry 3.5. *Journal of Management and Business Research*, 33(1), 87-103. DOI: 10.6504/JOM.2016.33.01.04

Chesbrough, H. (2006). Open innovation: A new paradigm for understanding industrial innovation. *Open innovation: Researching a new paradigm* (pp. 0-19). Oxford University Press.

International SEMATECH. (2003). *E-diagnostics and EEC guidance 2003*. SEMATECH, Austin, Texas.

Kagermann, H., Helbig, J., Hellinger, A., & Wahlster, W. (2013). *Recommendations for implementing the strategic initiative INDUSTRIE 4.0: Securing the future of German manufacturing industry; final report of the Industrie 4.0 Working Group*. Forschungsunion.

Li-Chih Wang, Shu-Kai Fan, Ching-Jung Ting, Tsai-Chi Kuo, Chun-Cheng Lin & Chia-Yu Hsu. (2018). The review of production system for advanced intelligent manufacturing. *Journal of Management and System*, 25(3), 381-412. ISSN:1023-9863

MacDougall, W. (2014). *Industrie 4.0: Smart Manufacturing for the Future*. Germany Trade and Invest.

Manyika, J. (2012). *Manufacturing the future: The next era of global growth and innovation.* McKinsey Global Institute.

McDermott, R., Mikulak, R. J., & Beauregard, M. (1996). *The basics of FMEA.* SteinerBooks.

Meng-Hsien Hsieh. (2015). *Smart Energy Sensor - Drive the Future of Applications in terms of Energy Saving, Energy Storage and Energy Creation.* Industrial Technology Research Institute. https://ieknet.iek.org.tw/iekrpt/rpt_more.aspx?actiontype=rpt&rpt_idno=576697908

Nenni, D. (2010, July 6). *TSMC extends open innovation platform.* Semiwiki. https://semiwiki.com/semiconductor-manufacturers/tsmc/462-tsmc-extends-open-innovation-platform/

Randall, R., Ramaswamy, V., & Ozcan, K. (2013). Strategy and co-creation thinking. *Strategy & Leadership*, 41(6).

Raynor, M. E., & Cotteleer, M. J. (2015). The more things change: Value creation, value capture, and the Internet of Things. *Deloitte Review*, 17, 51-65.

Sniderman, B., & Raynor, M. E. (2015). Power struggle: Customers, companies, and the Internet of Things. *Deloitte Review*, 17.

Shih, S. (1996). *Recreating acer-pioneering, growth and challenge.* Commonwealth Publishing Group.

Zack Hsieh, Chih-Hsun Lin, Ya-Chi Huang & Rain Yao. (2019). New technology services for energy management - the best solution for sustainable development of enterprises. https://ieknet.iek.org.tw/iekrpt/rpt_more.aspx?rpt_idno=224733856

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