A Flexible and Robust Production System against Changes in the Manufacturing Environment —Improving Operation with Yokogawa's AI Products—

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Many customers are seeking more flexible, robust operations to carry out various tasks at their manufacturing sites such as daily operations, KAIZEN activities, and troubleshooting, as well as to respond to changes in the manufacturing environment. For customers to achieve this, the process management method must undergo a paradigm shift, which is comparable to the invention of the DCS.

This paper introduces a new business model for optimizing operations and a function model for applying the business model to cope with changes in the manufacturing environment, and then describes a system architecture based on this function model and how Yokogawa's AI products work in the system.

INTRODUCTION

This paper proposes the concept of manufacturing operation supervision for achieving a production system that is resilient to changes in the manufacturing environment (the four "M"s: Material, Machine, Method, and huMan). The improvement activity presented in this paper targets customers' assets, optimizes their capabilities, and maximizes the economic value created by the assets. This activity does not bring in a new environment but makes the best use of existing four "M"s to adapt to severe environmental changes.

In the following sections, we will discuss customers' environments, changes in the operation environment, and digitalization as a way to respond quickly to the changes. We will then explain the technical concept of manufacturing operation supervision which is needed to solve problems in customers' environments. We will also introduce a system architecture to achieve the concept and Yokogawa's AI products to be used in the system.

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CUSTOMERS' ENVIRONMENTS

Changes in the Operation Environment

Production involves various activities of designing, manufacturing, and selling products of value that are of benefit to customers. In other words, production involves creating products from materials. Manufacturers earn profit from the difference between the economic value of the materials and that of the products. Therefore, to increase the profit margin, design, manufacturing, and sales strategies must maximize this difference. Manufacturing significantly increases the profit.

Since the operation environment at manufacturing sites has been changing, manufacturers are besieged by various challenges (Figure 1). In recent years, price competition has become more intense and thus more companies are seeking cheaper materials. However, even if materials sourced from various new suppliers manage to meet the acceptance criteria, they tend to vary greatly within the tolerance.

Companies do not compete only in terms of price. Some companies try to dominate the market by developing high-quality, cutting-edge products (materials) ahead of others. For such a strategy, the materials used in the product must meet customized specifications and strict quality standards.

Furthermore, the four "M"s of customers are constantly

changing. For example, aging equipment cannot keep performing at the level assumed at the design stage, leading to quality incidents and reducing the yield of acceptable products. In addition, when new workers replace retiring skilled ones, labor productivity may decrease, which also affects the four "M"s.
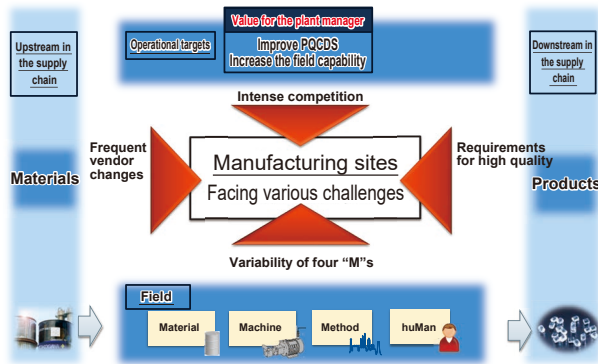

Figure 1 Changes in the operation environment

In the manufacturing industry, production design information that defines how to manufacture products is called a recipe (general recipes or master recipes) and manufacturing is carried out according to these instructions. As mentioned above, recipes should flexibly respond to changes in the four "M"s and external environment. However, changing a recipe greatly affects production; it requires replacement of equipment, verification of the changed design, and so on. Therefore, the design should not be changed frequently. As the four "M"s change continuously, it is difficult to manufacture products as expected at the design stage; this problem needs to be solved.

Digitalization

PQCDS is an acronym for product, quality, cost, delivery, and safety: the five keywords of production in the manufacturing industry. At the manufacturing site, it is crucial to provide a variety of products (P) that are needed by customers, with high quality (Q) and at low cost (C), with quick delivery (D) and safely (S). In addition to daily troubleshooting, KAIZEN activities are carried out to solve PQCDS issues at the manufacturing site. However, since the variability of the four "M"s and daily operations are also involved, it takes a long time to solve such issues. Digitization can be used to shorten this period.

Maturity of digitization

Focusing on digitization, acatech (the German Academy of Science and Engineering) provided a unified guideline for measuring its maturity (Industrie 4.0 Maturity Index Model [1]). The maturity is categorized into six levels (1) to (6) as shown in Figure 2.
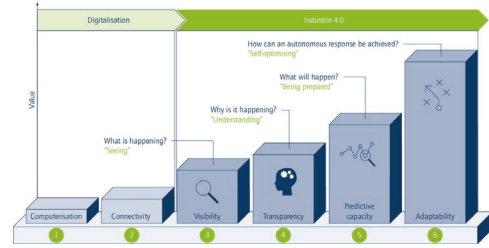

Figure 2 Maturity of digitization (source: acatech)

(1) Computerization
  Devices and equipment are computerized.
(2) Connectivity
  Computerized devices can exchange data via a network.
(3) Seeing
  The data are organized as information and operators can understand what is happening in the field.
(4) Understanding
  With sufficient accurate information about the situation in the field, operators can identify the causes of events in the field.
(5) Being prepared
  Operators can predict possible events in the field.
(6) Self-optimizing
  Operators can perform operations to recover from predicted events to the optimal production state.

Possibilities of solving problems through digitalization

Consider the time aspect of solving PQCDS problems. Figure 3 shows that a delay in solving problems decreases the value in the manufacturing site.

The horizontal axis in Figure 3 shows the time from occurrence of an event at the manufacturing site to its resolution. Some events can be recovered quickly, but others need a long time. An example of the former is recovering from defects found in the manufacturing process. An example of the latter is when a defect requires the modification of product specifications, as this will affect various processes (refurbishment, procurement, manufacturing, and so on). Solving PQCDS problems falls into the latter category.
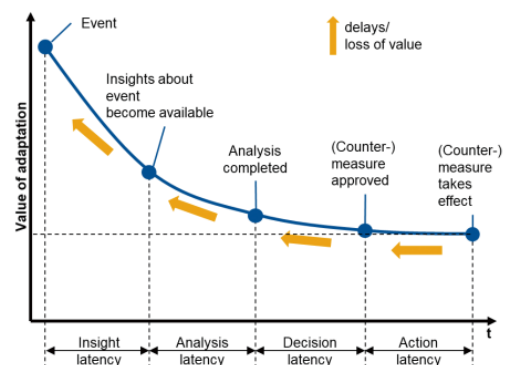

Figure 3 Time taken to resolve issues at the manufacturing site and the decrease in value (source: acatech)

When an event occurs at the manufacturing site, the delay continues until information about the event becomes available to those who need it for assessing the situation, such as equipment and device data. This also delays the response to the event. One reason is that separate systems which collect data and analyze them are not integrated seamlessly.

As shown in Figure 4, digitization can greatly shorten this delay. Its technical concept is shown below.
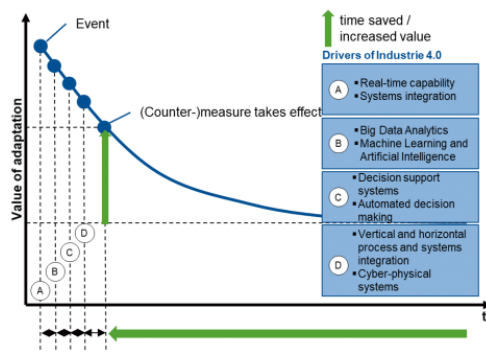

Figure 4 Digitization shortens the time for solving a problem and increases value (source: acatech)

(A) Shortening the time for insight

Computerize equipment and devices and connect all systems via the network. Achieve seamless, real-time data exchange and create an environment that offers the necessary information to those who need it at the right time.

(B) Shortening the time for analysis

Build an environment that collects data according to purposes and systematically analyzes what is happening in the field by using machine learning, AI, or other means.

(C) Shortening the time for decision-making

Introduce a decision-making support system that provides information to help understand the factors of an event.

(D) Shortening the time for response (action)

Build an environment that predicts future events based on the current (physical) situation. Virtually verify measures against predicted problems and use actual equipment and devices to deal with them.

As described in this section, in addition to carrying out their daily operations, customers must also solve PQCDS problems that occur due to changes in the manufacturing site. Therefore, they want to make their operations more resilient to changes. For customers to detect changes in the environment and respond flexibly, it is necessary to make a paradigm shift in process control by making full use of digitalization, which is comparable to the invention of the DCS.

A NEW NORM TO IMPROVE OPERATIONS

Yokogawa's solution to improve operations is positioned between the control layer and the manufacturing operations management (MOM) layer, in the functional hierarchy model of production systems defined in IEC/ISO62264. This service aims to achieve a flexible, robust production environment (systems and solutions) against the four "M" changes. For this purpose, Yokogawa uses digitalization and improves PQCDS in the manufacturing site.

One possible way to respond to the four "M" changes is to fundamentally overhaul the production design and four "M" resources. However, this would be extremely expensive and unable to respond quickly. Therefore, as shown in Figure 5, Yokogawa's approach is to allow for the variability of the four "M"s and changes in the external environment, fine-tune the existing manufacturing processes, and maintain the manufacturing conditions as expected. This solution aims to flexibly respond to environmental changes by optimizing the operation in the manufacturing site.
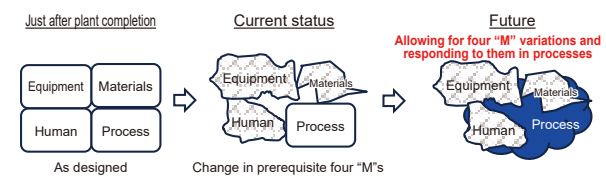

Figure 5 Optimizing operations while allowing for four "M" changes

Conventionally, manufacturing processes have been fine-tuned as a type of "reconciliation." However, since the quality of this approach depends on the operator's skills, it is difficult to obtain stable results over a long time. In addition, an increasing number of skilled workers are retiring, which makes it difficult to maintain stable conditions at the manufacturing site. Therefore, we propose a systematic (repeatable) means to replace this reconciliation.

First, we create an environment with which anyone can easily understand the state of the manufacturing process. Then, we build an environment that allows people to detect signs of abnormality and restore the process to the normal state at any time. We have built this systematic reconciliation environment as a system. As a result, customers do not need to invest in measures against four "M" changes and can concentrate their assets on achieving robust operation.

When such a production system resilient to four "M" changes becomes the new norm for operation improvement, penetrates the field, and helps make full use of customers' assets, experience, and knowledge in the manufacturing site, it is possible to maximize the economic value created by customers' production activity.

Task Model

A production system resilient to four "M" changes consists of two sub-systems: one is related to manufacturing operations (MOM and control) and the other maintains manufacturing conditions as expected amid variability of the four "M"s and changes in the external environment. The latter is called "manufacturing operation supervision." As shown in Figure 6, this system follows manufacturing operations carried out in the former system (MOM and control) and keeps

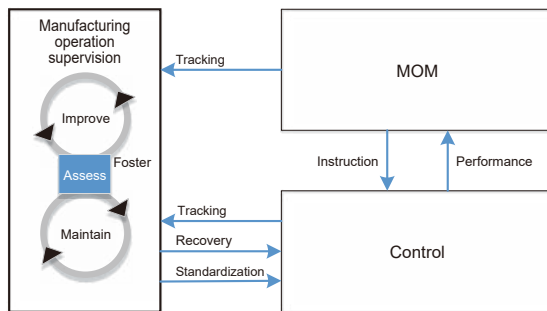the manufacturing in the optimal state depending on the state of the resources.

Figure 6 Positioning of the manufacturing operation supervision

As shown in Table 1, the tasks of the manufacturing operation supervision are the same as those for control but are carried out as a new norm and their contents are quite different. These tasks are outlined below.

(1) Designing to evaluate four "M" performance from the PQCDS perspective

Build a model to evaluate four "M" performance (the state of the four "M"s when the manufacturing conditions are maintained as expected) from the PQCDS perspective. In addition, improve the model to maintain four "M" performance in the optimal state from the PQCDS perspective, based on the results of the supervision capability analysis described below.

(2) Designing to visualize factors of four "M" performance deterioration

Design a decision tree to identify the factors of four "M" performance deterioration (extreme deviation of four "M"s). The decision tree explains the factors of each of the four "M"s in a hierarchy based on their causal relationships. These factors can be understood by following this hierarchy.

(3) Defining the four "M" performance recovery operation

Define an operation to restore four "M" performance to a stable state. In this operation, experience, knowledge, and PQCDS constraints at the manufacturing site are examined and the most suitable one is used to recover four "M" performance.

Table 1 Task model of the manufacturing operation supervision

Category		Control (Existing norms)	Manufacturing operation supervision (New norms)
Major category	Sub-category		
Design, implementation, verification	Definition management	Design of manufacturing process execution flow Design of physical process control logic Design of procedures for monitoring and operating the manufacturing process Design of manufacturing process control	(1) Designing to evaluate four "M" performance from the PQCDS perspective
	Configuration management	Adjustment of field equipment and maintenance and management of set values	(2) Designing to visualize factors of four "M" performance deterioration
	Implementation management	Implementation in the control system Verification of implemented functions	(3) Defining the four "M" performance recovery task
Execution	Task execution management	Sequential execution of the business logic embedded in the manufacturing process	(4) Evaluating four "M" performance (5) Understanding the factors of four "M" performance deterioration and making decisions
	Control	Monitoring and control of physical processes	(6) Recovering four "M" performance
Analysis	Data collection	Collection of data for process control and failure and performance analyses	(7) Collecting and processing four "M" data for evaluating performance
	Task analysis	Quality analysis of process capabilities and deliverables	(8) Analyzing supervision capacity
	Task tracking	Tracing the results of process execution and analysis Providing feedback to the design team	(9) Fostering supervision capability

(4) Evaluating four "M" performance

Evaluate four "M" performance from the PQCDS perspective using the evaluation model developed in task (1). Evaluate each manufacturing instruction and determine whether four "M" performance has deteriorated.

(5) Understanding the factors of four "M" performance deterioration and making decisions

When the deterioration of four "M" performance is predicted, understand its factors and take measures to stabilize it. Use the decision-making information designed in tasks (2) and (3) to understand the causes of failure. Recovery operations that take PQCDS constraints into account become available (displayed) as options. It is possible to carry out the most appropriate action among them.

(6) Recovering four "M" performance

Perform an operation to restore four "M" performance. The operation may be carried out manually, semi-automatically, or automatically.

(7) Collecting and processing four "M" data for evaluating performance

Collect four "M" data including manufacturing instructions, process values, material properties and usage, equipment status, product quality, and external data. Process the data to calculate four "M" performance for evaluating PQCDS.

(8) Analyzing supervision capability

Analyze whether the capability of the model developed in task (1) to evaluate four "M" performance reaches the target level (e.g., whether the discrimination rate is at the same level as at the start of the evaluation with the model).

(9) Fostering supervision capability

Tell the design team to improve the evaluation model if the analysis in task (8) shows the model is ineffective.

Functional Model

Figure 7 shows the key functions for manufacturing operation supervision. Table 2 shows the relationship between these functions and the operations listed in Table 1. Each function is outlined below.
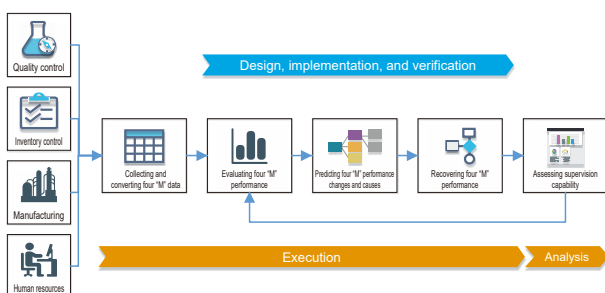

Figure 7 Functions of the manufacturing operation supervision

Table 2 Relationship between functions and the task model

Function	Operations involved in the task model	
	Design, implementation, verification	Execution and analysis
(1) Collecting and processing four "M" data		Collecting and processing four "M" data for evaluating performance
(2) Evaluating four "M" performance	Designing to evaluate four "M" performance from the PQCDS perspective	Evaluating four "M" performance
(3) Predicting four "M" performance changes and causes	Designing to visualize factors of four "M" performance deterioration	Understanding the factors of four "M" performance deterioration and making decisions
(4) Recovering four "M" performance	Defining the four "M" performance recovery operation	Recovering four "M" performance
(5) Assessing supervision capability		Analyzing supervision capacity Fostering supervision capability

(1) Collecting and processing four "M" data

The manufacturing operation supervision covers a wide range of data such as control, manufacturing execution management, and quality control. Since the characteristics and methods of collecting the data are so diverse, it is difficult to use the data as they are. Therefore, this function standardizes ways to collect and disclose data to make it possible to process and use data for respective objectives in execution and analysis tasks.

(2) Evaluating four "M" performance

There are two functions for evaluating four "M" performance: one builds an evaluation model to determine four "M" performance deterioration at the design stage, and the other determines such deterioration during runtime using the model.

When four "M"s are changing, it is difficult to explain four "M" performance with a single factor. Therefore, this function uses AI technology to detect abnormalities in multi-dimensional data. However, operators at the manufacturing site will not be satisfied with results if these ignore the causal relationships between four "M"s and physical processes. The manufacturing operation supervision provides a data profiling function that can determine explanatory variables for objective variables based on the process skills, chemical engineering skills, and operating skills at the manufacturing site. This makes it possible to build a highly useful evaluation model for customers.

(3) Predicting four "M" performance changes and identifying causes

This function designs a decision tree to determine the factors of four "M" performance deterioration at the design stage. When such deterioration is detected during runtime, possible causal factors are evaluated one by one.

The circumstances of four "M" performance deterioration are constantly changing, and so the factors of deterioration are also always changing. As shown in Figure 8, this function assesses how much each factor contributes to the deterioration in view of the situation both at the design stage and during runtime. This limits the scope and priority of analysis for the causes of deterioration and thus narrows down the causes of failures. Note that in this process it is necessary to consider not only the dynamic contribution but also the static importance (importance from the design perspective). Therefore, the final evaluation that the manufacturing operation supervision gives as a new norm reflects the principle and actual status of four "M" performance.
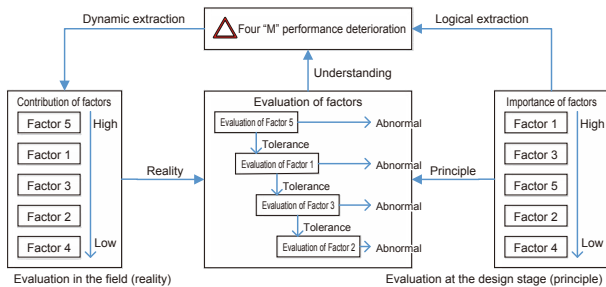

Figure 8 Understanding the factors of four "M" performance deterioration

(4) Recovering four "M" performance

This function defines a recovery operation at the design stage to restore four "M" performance. For the operation during runtime, the optimal operation that recovers four "M" performance is selected from among experience, knowledge, and PQCDS constraints at the manufacturing site and then executed.

The recovery operation is recorded in a document or implemented as a repeatable procedure in the computer. In the latter case, the recovery operation is written in Domain Specific Language (DSL).

(5) Assessing supervision capability

This function evaluates whether the judgement capability of the evaluation model satisfies the target level. When it is below the target, the evaluation model is re-created by taking into account the current manufacturing situation to strengthen the manufacturing operation supervision.

Implementation Model

Figure 9 shows the system architecture of the manufacturing operation supervision. This architecture is based on the Industrial Internet Reference Architecture (IIRA)[2]. The tasks described in the "Task Model" section are assigned to four basic domains. In addition, components that implement the functions described in the "Function Model" section are allocated in each domain. For the overall system topology, the three-layer architecture model introduced in IIRA is adopted.

(1) Automation Domain

Performs all operations from planning of production to its execution. Data generated in this domain are provided to the Information Domain for improving operations.
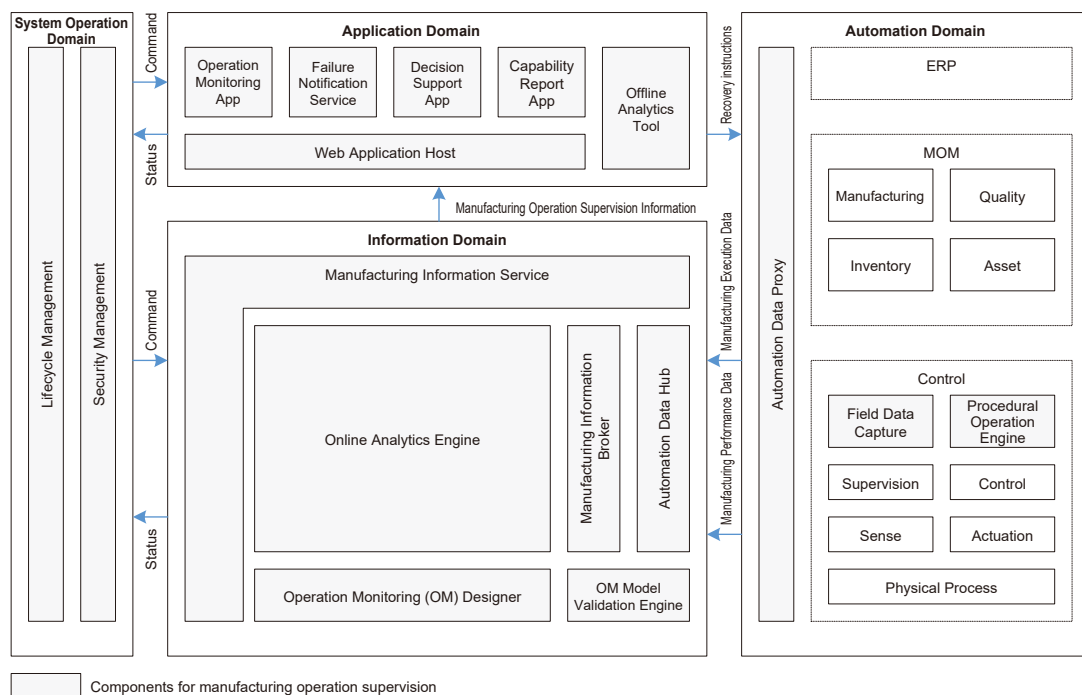

Figure 9 System components

(2) Information Domain

Generates information from manufacturing data to evaluate four "M" performance from the PQCDS perspective. Makes the information available so that it can be used in other domains.

(3) Application Domain

Takes the responsibilities of the manufacturing operation supervision (task model) based on the information generated in the Information Domain.

(4) System Domain

Keeps the manufacturing operation supervision running.

The functions indispensable for the manufacturing operation supervision, which are introduced in the "Functional Model" section, are implemented as applications in the Application Domain as shown in Table 3. This is not a monolithic system but a combination of systems with well-defined competencies. In other words, existing and new autonomous systems are integrated for the purpose.

Table 3 Relationship with the functional model

Functionality	Applications
Evaluating four "M" performance	Operation & Monitoring Service, Failure Notification Service
Predicting four "M" performance changes and causes	Decision Support Service
Recovering four "M" performance	
Assessing supervision capability	Performance Report Service

By systematizing the functions in this table, we can offer a product that provides manufacturing operation supervision. With this product, we can clarify what investment is necessary to achieve the customer's goal from the perspective of digitalization and show its effects from the perspective of manufacturing operation.

AI PRODUCTS TO BE USED IN A PRODUCTION SYSTEM RESILIENT TO FOUR "M" CHANGES

Table 4 shows the functions presented in the "Functional Model" section allocated to the maturity of digitalization and the technical concept to achieve digitization. To make full use of digitization to eliminate the delay in resolving PQCDS problems, it is necessary to introduce a system that collects and analyzes data. In the manufacturing operation supervision, this system is achieved by the functions of 1) collecting and processing four "M" data and 2) evaluating four "M" performance. These two functions have been implemented in two products: Digital Plant Operation Intelligence and Process Data Analytics.

Table 4 Manufacturing operation supervision and the maturity of digitalization

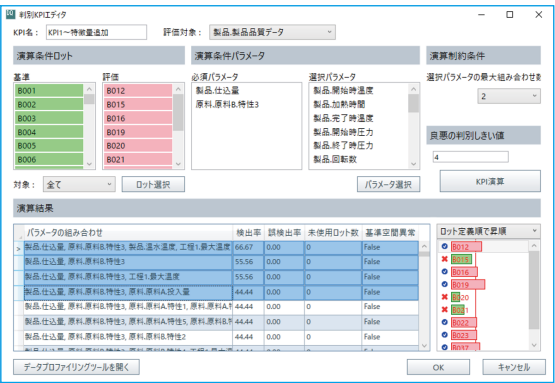| Maturity of digitalization		Technical concept of digitization	Functions of the manufacturing operation supervision
High	Self-optimizing	Shortening the time for response (action)	Recovering four "M" performance
	Being prepared	Shortening the time for decision-making	Predicting four "M" performance changes and causes
	Understanding	Shortening the time for analysis	Evaluating four "M" performance
	Seeing	Shortening the time for insight	Collecting and processing four "M" data
	Connectivity		
Low	Computerization		

Digital Plant Operation Intelligence

Digital Plant Operation Intelligence is a quality stabilization system that analyzes four "M" data stored in a customer's plant and detects signs of deviation from the quality required by the customer. As shown in Figure 10, this system can handle various data, such as temperature, flow rate, and other data stored in the plant information management system (PIMS) and quality and material data stored in the laboratory information management system (LIMS).

Figure 10 Four "M" data input

In addition, the analytical data profiling function uses the Mahalanobis-Taguchi (MT) method, which is an AI technology. As shown in Figure 11, this function selects the input parameters (explanatory variables) based on the process skills, chemical engineering skills, and operating skills at the manufacturing site and determines how much each input parameter affects the target event. Therefore, it is possible to create an evaluation model with process capability that satisfies customers. This model is used to evaluate process capability. By monitoring the evaluation results during

runtime, it is possible to detect signs of deviation from the required quality and help take measures to prevent such deviation.

(Overseas versions are under development.)

Figure 11 Creating a model for evaluating the process capability

Process Data Analytics

Process Data Analytics is analysis software designed and developed based on Yokogawa's know-how obtained from more than 100 analysis consulting projects. This software has various functions. As shown in Figure 12, it handles process data such as temperature, flow rate, and liquid level stored in PIMS, as well as operational data such as alarms and operation history, and collates and checks changes in process data and those in materials and operating conditions. It also has a function to stratify and compare the quality inspection results and operating conditions. These enable operators to organize the process data together with four "M" information.
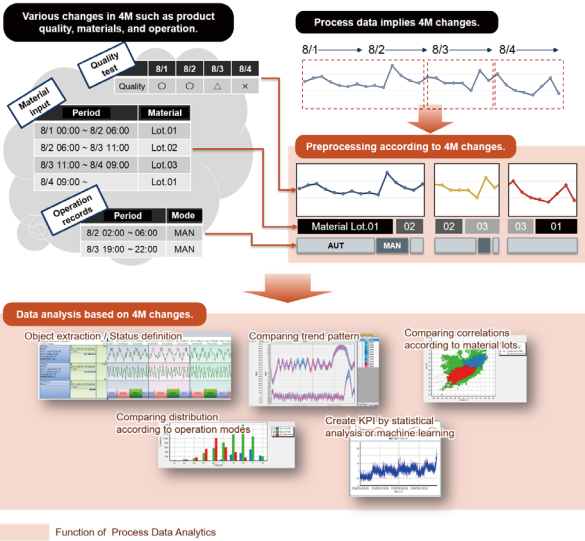

Figure 12 Function of Process Data Analytics to organize data

Just like Digital Plant Operation Intelligence, Process Data Analytics also has an analysis function that uses the MT method. Since huge amounts of process data are involved in a continuous process, it is difficult to identify the causes of quality and process abnormalities. As shown in Figure 13, Process Data Analytics can analyze complex continuous processes with a model that uses the Mahalanobis distance (MD).

In addition, this software can easily incorporate various AI techniques of MATLAB, numerical analysis software of The MathWorks, Inc., into the evaluation model.
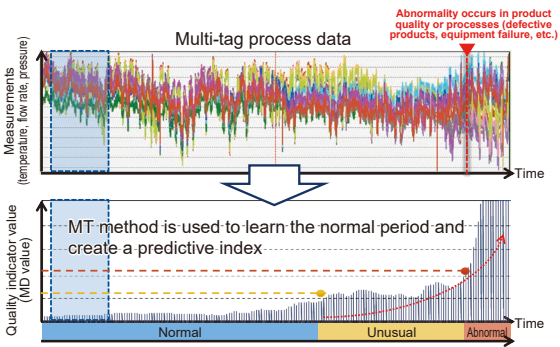

Figure 13 Evaluation of a process capability model using the MT method

CONCLUSION

This paper introduced manufacturing operation supervision, which will become the new norm for improving operations by resolving the challenges in manufacturing sites and responding to the ever-changing manufacturing environment. By building a production system that is resilient to four "M" changes, it will be possible to make full use of assets, experience, and knowledge at the manufacturing site, as well as maximize the economic value created by our customers' manufacturing activities. We will continue to develop new products to make our production systems resilient to changes.

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(1) G. Schuh, R. Anderl, et al., "Industrie 4.0 Maturity Index," National Academy of Science and Engineering (acatech), 2017
(2) IIC, "The Industrial Internet of Things Volume G1: Reference Architecture," Version 1.9, 2019