A Digital Factory Approach to Data-driven Management in Factories

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Yokogawa's solutions and know-how play an important role in accelerating digital transformation (DX) of operational technology (OT) in the manufacturing industry. When proposing these solutions and know-how to customers, it is persuasive to be able to show that Yokogawa has actually improved productivity in its own factories using its OT operations data. This specific example will help customers to understand the effectiveness of the proposal. To achieve data-driven management with OT operation data, three requirements must be satisfied: (1) OT Data Lake, which is a framework for gathering operational data from Yokogawa's factories worldwide into a single database and improving productivity on a global scale, (2) AI optimization and automation that use operational data and images, and (3) remote operation that ensures the continuity of business even when people's access is restricted, for example, due to the COVID-19 pandemic. Yokogawa defines a factory that satisfies these three items as a Digital Factory and is working hard to make its own factories as such. Although this approach is one of Yokogawa's Internal DX measures, the results can be used to develop know-how for External DX, which will increase value for customers, expedite DX in existing businesses, create new DX businesses, and strengthen Yokogawa's presence in DX. This paper introduces Yokogawa's approach to Internal DX, its roadmap, and progress toward external DX.

INTRODUCTION

The Industrie 4.0 initiative, which started in Germany in 2012, has promoted the digitalization of the manufacturing industry and revolutionized its business models. Manufacturing is shifting from the traditional vertically integrated model to a networked model based on process collaboration among companies through de jure standardization and openness. The Industrie 4.0 Platform (PI4.0), a promotion organization run by the German electrical, telecommunications, and machinery industries (BITKOM, VDMA, ZVEI), published Reference Architecture Model Industrie 4.0 (RAMI4.0) to achieve Industrie 4.0 (Figure 1).

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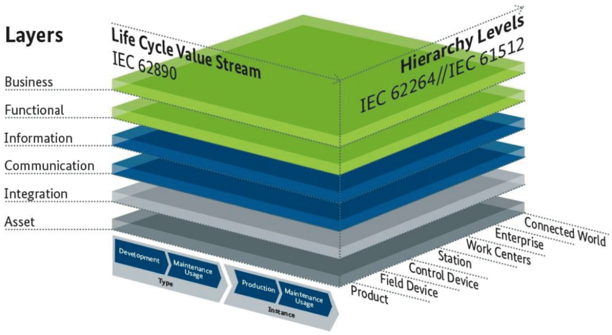

Figure 1 Structure of RAMI4.0[1]

Regarding standards that can be used as implementation models, the RAMI4.0 intends to use them as they are where possible. The right side in the figure (Hierarchy Levels: IEC62264/IEC61512) corresponds to the operational technology (OT) domain and is based on the concept of ISA-95 (IEC62264). ISA-95 is an international standard for integrating manufacturing and management systems (Figure 2). In this standard, the structure of the production management system is layered with the planning layer (Level 4: ERP), manufacturing execution layer (Level 3: MES/MOM), control layer (Level 2: DCS, SCADA), and equipment (Levels 0 and 1: sensors/manipulators, PLCs). The interface between these layers is prepared for production management standardization indexes such as ISO22400. KPIs are defined in six areas: productivity, quality, capacity, environment, inventory control, and maintenance.

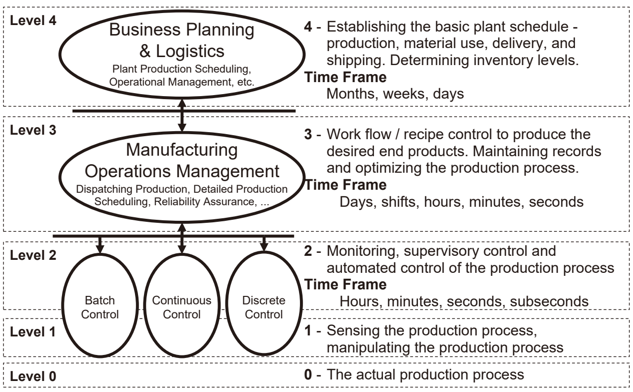

Figure 2 ISA-95 functional hierarchy[2]

The correlation among standards in smart manufacturing is as follows (Figure 3).

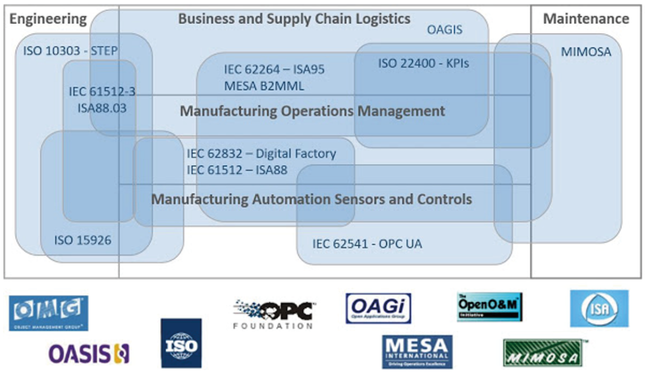

Figure 3 Multiple data exchange standards covering the smart manufacturing landscape[3]

In addition to establishing these international standards, the German government has established an industry-government-academia partnership through the Industrie 4.0 Platform and has been working on global standardization. Participating organizations include government agencies related to the economy, energy, and education and research; industry associations such as BITKOM, VDMA, and ZVEI; research institutes such as the Fraunhofer-Gesellschaft; and private companies such as BOSCH.

In contrast, in the U.S., the private sector led the establishment of the Industrial Internet Consortium (IIC) in 2014. The IIC is an open consortium in which private companies, educational institutions, and government officials participate. It works together with many other organizations including Industrie 4.0. As a result, a wider variety of industries have joined the IIC than Industrie 4.0. Industrie 4.0 is an organization mainly for the manufacturing industry, whereas the IIC covers a wide range of industries such as healthcare, energy, smart cities, and transportation.

In Japan, the government started in 2015 to fully support the development of digital technologies such as the Industrial Internet of Things (IIoT) and AI, which are expected to create new value. In response to the policies of China (China Manufacturing 2025) and India (Make in India), the Ministry of Economy, Trade and Industry (METI) is promoting industrial collaboration with other countries and is leading cross-industrial collaboration in Japan and overseas ("connected industries"). Each industry and company has also been actively engaged in similar efforts since around 2015. Many companies are digitizing their manufacturing sites and visualizing their factory operations based on accumulated data. By connecting these data, they are also working on smart factories that will improve productivity.

Yokogawa is also working hard to build the OT Data Lake, which not only connects data within a single factory but also gathers data from multiple factories worldwide into a single database and integrates OT data. This system is the foundation for improving productivity and achieving data-driven operations in its own factories around the world. This initiative aims to differentiate Yokogawa from competitors and create a new data-driven business model based on its proprietary data.

To achieve the Digital Factory, we are taking three measures: (1) construction of the OT Data Lake, (2) automation by using the operational data and images in the OT Data Lake, and application of artificial intelligence (AI) and machine learning (ML) technology to quality control processes, and (3) remote operation of factories to enable business activities to continue even in an environment in which goods are allowed to be transported but human movement is restricted, such as the COVID-19 pandemic. The following sections outline their configuration and related efforts.

OUTLINE OF DIGITAL FACTORY

First, we defined the current state of the factory (As-Is) and the ideal state (To-Be).

The As-Is is a human-driven operation in which operational data is not linked within a factory and among factories, and operations are based on tacit knowledge, master techniques, and know-how of human operators at manufacturing lines. The To-Be consolidates operation data in factories around the world into a single database, builds an OT integration environment, and achieves data-driven operations that make decisions and take actions based on data. The difference between these two states is clear in the following five items (Table 1): handing down skills and techniques, accumulating and applying production technology, improving quality and productivity, KAIZEN and innovation, and supply chain management (SCM).

Table 1 As-Is and To-Be of factories

	As-Is	To-Be
Handing down skills and techniques	Operation of production lines depends on judgments based on tacit knowledge, mastery skills, and experience.	Line operation techniques are passed on digitally. Make tangible the tacit knowledge, mastery skills, and personalized operations, and use AI and ML to make decisions.
Accumulating and applying production technology	Personalized. Difficult to accumulate and apply production technology due to aging population	Digitally accumulating line operation techniques Make tangible the know-how of the production line and apply it to other factories.
Improving quality and productivity	Strong tendency of partial optimization rather than total optimization	Improving quality through total optimization using AI and the IIoT, and improving productivity through automation and labor-saving
KAIZEN and innovation	Partial activities based on personal knowledge and experience	Accelerating KAIZEN and creating production innovation by combining data
SCM	Prediction based on experience. Individual judgment and optimization of inventory	Achieve total optimization through cross-departmental and environment-responsive management of operations.

The OT integration environment is built in the cloud, and this environment serves as the OT Data Lake. In the ideal state of a factory (To-Be, or the Digital Factory), the OT Data Lake is realized, AI/ML technology combined with operational data in the OT Data Lake and IIoT data is applied to the quality control process, and remote operation that promotes new ways of working is achieved (Figure 4).

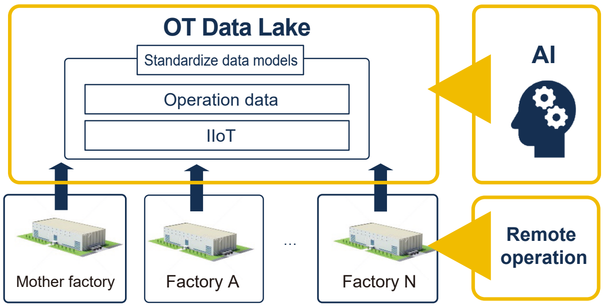

Figure 4 Ideal state of a factory: To-Be or Digital Factory

Next, we discuss the development of Internal DX starting from the Digital Factory (Figure 5).

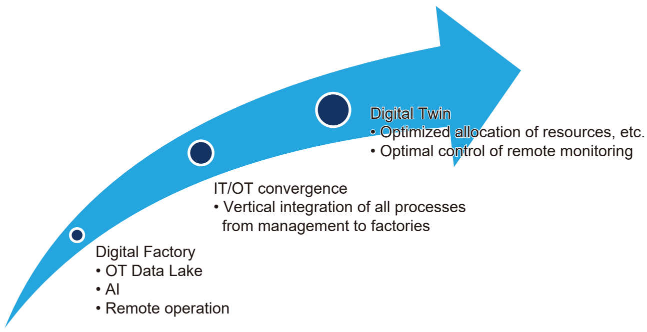

Figure 5 Internal DX starting from Digital Factory

Although the main purpose of the Digital Factory is to integrate OT, the ultimate goal is to integrate IT and OT. Coordination with the IT domain also means coordination with ERP. This links the data in all processes from the management level to the production floor (Figure 6).

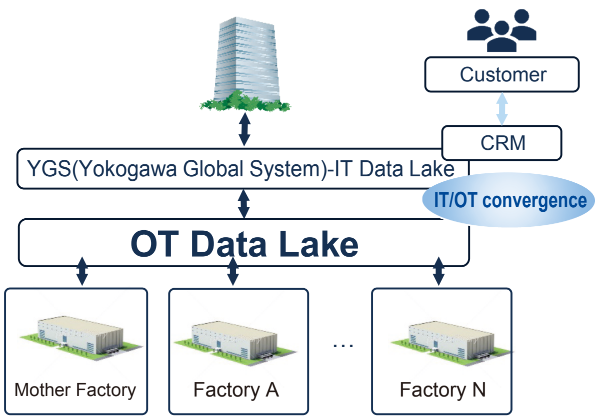

Figure 6 IT/OT convergence

The data in the OT Data Lake will be standardized using a common data model (described later). The IT/OT convergence in all the processes from the management level to the factory using the standardized data will achieve quick decision-making and expand business opportunities through customer relationship management (CRM). In addition, this integration will make it possible to build the Digital Twin, which will optimize operations including resource allocation at offices and factories around the world. The Digital Twin can perform enterprise-level simulations and virtually represent physically existing assets, processes, and resources. This serves as a mechanism to achieve remote control of factory equipment. The details of the Digital Twin are described later.

The organizational structure for achieving the Digital Factory is as follows. These initiatives are promoted under the cooperation of Yokogawa's Digital Strategy Headquarters and Yokogawa Manufacturing Corporation. We import a factory's operational data into the OT Data Lake, create scenarios for improving productivity, and use data to visualize factory operations such as the progress of processes and energy consumption, identify waste, shorten lead-times, and improve productivity.

To apply AI/ML technology, we set up a development base at Yokogawa IA Technology India (Bengaluru, India). This base is working with Yokogawa Electric CIS Ltd. (Moscow, Russia) and factories around the world to tackle this task.

Remote operation at factories is promoted in cooperation with the IT staff at each site and field workers in each factory. This activity is being carried out as a global measure with a view to not only the working conditions under the influence of COVID-19 but also the post-pandemic business environment.

The following sections describe each of the three initiatives in detail.

OT Data Lake for Data-driven Operations in Factories

Architecture

The OT Data Lake is built on Azure, a cloud solution from Microsoft. Its infrastructure consists of the Gateway (G/W) layer, Interface (IF) layer, Data Lake layer, Preparation layer, Data Warehouse/Data Mart (DWH/DM) layer, and Application layer. The Azure-based OT Data Lake offers various PaaS services and transports various data from the data source to the DWH/DM layer. Since the OT Data Lake handles factory data and images, it must use a virtual network and each PaaS service securely within the intranet. Each PaaS service uses the Service End Point, Private IP, and Azure Private Link provided by Azure. This environment does not allow direct access from the outside via the Internet. In addition, the OT Data Lake uses the lambda architecture as a way to process huge amounts of data. The obtained data then flow to either the batch layer or the velocity layer. The path to the batch layer is called the cold path, where factory data are obtained as they are through periodic batch processing. The path to the velocity layer is called the hot path, which handles streaming data and enables real-time monitoring and analysis.

In terms of functionality, the OT Data Lake consists of three databases: Data Lake DB, Common DB, and Analysis DB. Each database has the following roles (Figure 7).

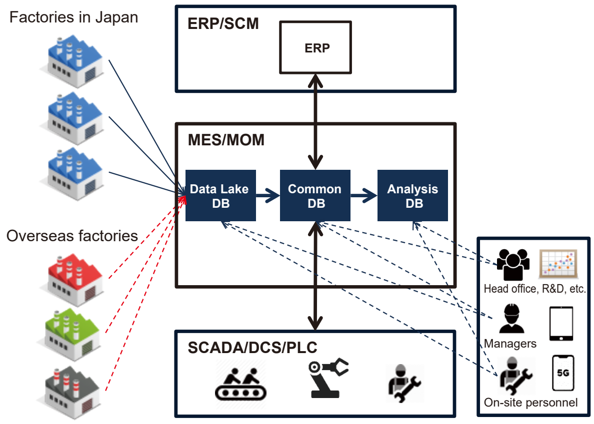

Figure 7 Positioning of the three databases

The Data Lake DB collects raw data from databases (Oracle, etc.) on the edge server of each factory. The raw data are of different granularity and frequency, and thus time data, location data, and other metadata tend to contain differences and errors. Therefore, these data need to be stored and then normalized. The Data Lake DB digitizes and stores all kinds of raw data, such as environmental data that keep changing, numerical values that vary due to differences in equipment and performance, and images and sensory data.

The Common DB is tied with a common data model (described later). The data to be stored are normalized by a standard language and concept while the relationships defined in the common data model are retained. The database also stores data properties as metadata. In this way, the data in the manufacturing execution system (MES)/manufacturing operations management (MOM) (Level 3) are normalized in the defined class and collected while their relationships are retained. These are materialized and standardized based on ISA-95 (IEC62264). This improves the accuracy of the enterprise resource planning (ERP) at Level 4 and the planning and management of facilities and equipment at Levels 0 and 2, and also clarifies the data correlation for each class. This database plays a central role in achieving the Digital Factory. It covers the integrated data for the entire company, which the head office needs for data analysis while the research departments and product development departments need the data for developing products.

The Analysis DB stores the data from the Common DB and Data Lake, which are necessary for applications and have already been calculated. This database is used for executing tasks such as routine reports/ad hoc reports, visualization, progress management, and KAIZEN by optimization. Users (people in the head office and research/product development departments, managers, and persons in charge of the field) can use this DB to draw up reports and perform other data processing tasks. The Analysis DB is also used by data analysts.

Common data model

Standardization is essential to consolidate operation data in factories around the world into a single database and use them as a basis for improving productivity globally. With an eye to IT/OT convergence, we focused on ISA-95 (IEC62264), which has an interface between the ERP and MES layers. The scope of ISA-95 is the interface between the MOM area (Level 3) and ERP (Level 4). The details of DCS, sensing, and other items (Levels 1 and 2) are handled by other standards. Since standardization has been discussed extensively in the OT industry, the scope of ISA-95 has become wider and more abstract. Therefore, we mapped the actual data of Yokogawa's factories to the model shown in ISA-95, conducted fit-and-gap analysis, and worked on materializing properties (attributes of data). We are also working on items in Levels 1 and 2 so that the data model can handle all data in a factory.

When ISA-95 was first discussed, it seemed to focus on the MES domain (Level 3). Considering the recent progress in the IIoT, however, we believe that Levels 1 and 2 should also be discussed. The construction of this data model will play an important role in the integration of OT data, and then of IT and OT. By linking this data model with the Common DB, we are vertically integrating all processes from the management level to the production floor.

Application of AI/ML Technology to the Quality Control Process in Factories

The introduction of AI in factories aims to save manpower through automation and eliminate the dependency on human skills, knowledge, and expertise. In many factories, multiple visual inspections are performed to detect defective parts and products. This process requires inspectors to have high-level skills. To improve the efficiency of this process, we are digitizing part of the visual inspection process by using AI/ML and other technologies.

The most important point in implementing AI/ML solutions is data availability, and all possible combinations of data patterns (teacher data) are fed to the ML algorithm. In visual inspections, inspectors usually classify defects based on their experience and knowledge. Therefore, for the algorithm to learn such defect patterns, a large number of samples representing each pattern are required. However, the rate of defect incidences is very low due to constant improvements in factories, and thus it is practically impossible to obtain all patterns from images to create a classification model. Therefore, we took the following measures.

- Use only images of good sensor chips as good patterns.
- Analyze the already defined patterns of defects and generate images that contain defective patterns. Use these images as input and build a classification model with a neural network.

With this method, we are modeling the acceptable and defective patterns of parts and products, which have many variations. The application of these AI/ML technologies is effective not only for saving manpower but also eliminating the dependency on human skills and expertise, achieving stable and consistent inspection results.

We are also developing total quality optimization, which acquires data from a wide range of areas, from upstream to downstream of production lines, and analyzes factors that cause yield loss in the final inspection. For this project, we are working together with the R&D department and product development departments in business units. The details are described in the section "Expansion to External DX."

Remote Factory Operations

The COVID-19 pandemic demands companies to ensure employee safety and restrict movement of human workers. Under these conditions, essential workers and all other employees are required to adopt new ways of working. To create an environment for remote operations, we adopted wearable devices and other new technologies (Figure 8).

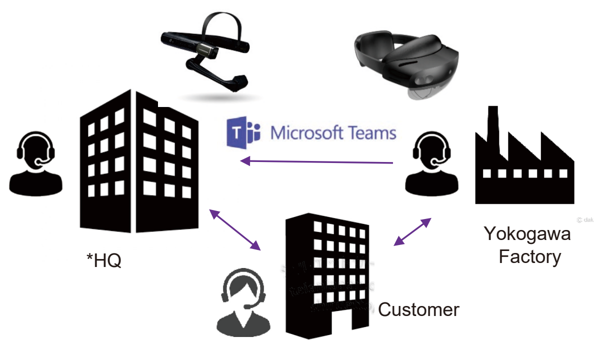

Figure 8 Remote operations

Remote operations using voice-enabled devices are being tested for practical use. Some examples are shown below.

- Factory acceptance tests are conducted with customers in remote places.
- How Yokogawa products are working in the factories of other customers and Yokogawa is showcased to remote customers.
- Development personnel in remote, different places work together to develop products and solutions.

Remote operations not only enable smarter, faster, and more sustainable ways of working in a DX style, but also shorten working hours, reduce costs, and improve resource management.

Currently, technologies such as augmented reality (AR), virtual reality (VR), and mixed reality (MR) are being used to accelerate remote operations. These efforts can provide manufacturing operation support, remote maintenance, and remote training for workers (manufacturing operation support aims to reduce the burden of checking readings on instruments and human errors that occur when decisions are made based on uncertain memory). We are also trying to digitize and standardize the know-how of experienced workers for complex piping and wiring tasks that are difficult to be described in drawings. It will be possible to provide feedback to upstream product development departments, reducing costs. In addition, remote operation is expected to be applicable to an even wider range of fields, such as original design manufacturing (ODM).

FUTURE DEVELOPMENTS

The previous sections introduced the Internal DX initiative, which aims to improve productivity within Yokogawa. The following section introduces External DX, referring to an example of the Digital Twin. This initiative aims to develop solutions for customers based on the knowledge and know-how cultivated in Internal DX.

Digital Twin

We set the three growth stages of the Digital Twin (Figure 9).

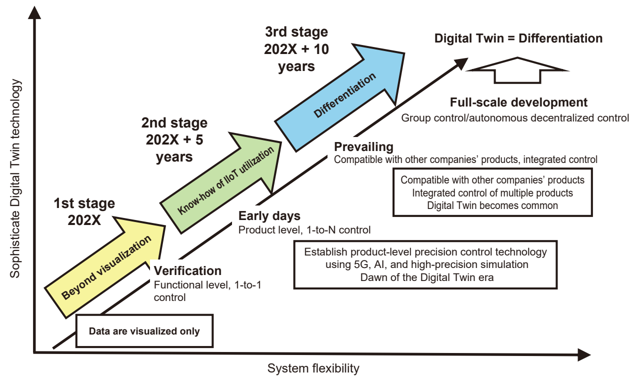

Figure 9 Three growth stages of the Digital Twin

We are currently in the first stage, where activities focus on promoting the IIoT and visualizing data. There are several scenarios for utilizing the data and we are steadily moving towards the second stage. To reach the final form of the Digital Twin, we must successfully finish the first stage ("beyond visualization") and verify and acquire technologies for at least one-to-one remote control between a monitoring system and production facilities. Technologies obtained in this stage will determine the success of the following stages.

In the second stage, we aim to achieve 1-to-N control, where multiple production facilities are monitored from a single location. Control must cover a wider range, i.e., the system level for total optimization. To achieve this, it will be necessary to utilize 5G high-speed communication technology that enables remote control; simulation technologies for analyzing fluids and heat transfer; AI that eliminates the need for empirical rules and dependency on individual skills; and AR, VR, and MR technologies for 3D modeling of factories. The Digital Twin represents actual equipment assets, processes, and resources in virtual space. To express the facility area of a factory with the Digital Twin, we will need a 3D model of the area (Figure 10). Since a solution that converts captured images into a 3D model is already available, we can create a factory utility in a virtual space by combining this solution with IIoT data.

Figure 10 Example of 3D modeling (back office)

Standardization may be the key to the third stage. We are planning to create an integrated control environment, which can also cover products from other companies.

Expansion to External DX

The previous sections introduced the Digital Factory with a focus on Yokogawa's own factories. The author has drawn up a scenario for utilizing data and improving productivity, selected and installed IIoT sensors, and provided feedback on the results. We can propose to users the experience, knowledge, and know-how we have gained through these efforts. This is Yokogawa's strength and a completely different way of doing business from simply selling applications that may be available in the market. In the course of activities at our own factories, we found the usefulness of an OT Data Lake application: collaboration between factories and R&D/product development departments. Data from the company's own factories are valuable in product development. The OT Data Lake allows them to be used immediately. This environment will reduce the number of man-hours, shorten the product development period, reduce the initial investment, and improve the quality. We are collaborating with several research and development departments to promote the use of factory data. Products and solutions resulting from this activity will make Yokogawa more attractive to customers. Factories will serve as a showroom for customers. We believe that we will soon be able to make attractive proposals to customers based on our experience, knowledge, and know-how accumulated through Internal DX activities.

CONCLUSION

This paper introduced the global trend of data integration and standardization, the role of the OT Data Lake in achieving data-driven operations in factories, application of AI/ML technology to quality control processes in factories, the significance of remote operations, and activities to turn our insights into business proposals to customers. We hope that these efforts will help Yokogawa to improve productivity and develop new business models, and that our experience, knowledge, and expertise will help customers with their operation.

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