Series
Toward Realization of Smart Manufacturing Systems

Case: A cyber-physical manufacturing system enhanced with collective knowledge

Robot Revolution Initiative
WG for manufacturing business revolution through IoT
The Industrial Machinery Steering Committee

March 2017

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Supported by

METI Ministry of Economy, Trade and Industry　JMTBA

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1. Overview

(1) Proposals

In this year, the Industrial Machinery Steering Committee has prepared the following proposals.

- ○ It proposes the concept of smart manufacturing to which “Kaizen” on the production engineering side including on-the-job sites is reflected as a cyber-physical manufacturing system. (While international attention towards smart manufacturing is increasing, the above concept considering “Kaizen” has not been well discussed so far.) As the approach for promoting the discussion about the above concept, it proposes a model-based approach to investigate information flows in the cyber-physical manufacturing system including human judgment, clarifies the mechanism for reflecting human judgments in the cyber space, and tries to analyze the data items exchanged by the machine tools with the production management side by using specific use cases.

- ○ To realize the above concept in a secure environment, it proposes a procedure to localize problems on information leakage based on the information model and use case analysis, while considering the relationship among the stakeholders of the business conducted in the cyber-physical manufacturing system and the characteristics of the information exchanged.

Based on our activities, we would like to promote international collaboration toward realization of smart manufacturing, in which the standardization of interface of machine tools as the core components of cyber-physical manufacturing systems is regarded as an example of such collaboration.

(2) Organization

The Committee consists of the business practitioners who carry the strategies of the overall industry from machine tool manufacturers, control device manufacturers, and machine tool users. In order to continue the last year’s discussion, this year, in addition to the Committee, the working group to investigate machine tool interfaces based on the concept proposed by this Committee was formed. The members of the working group were chosen from the member companies of this Committee. Based on their background, the members are able to discuss specific models and use cases. This report shows the member list of this Committee and the working group at the end.

(3) Outline

This year, the Committee and working group mainly conducted the following activities. Firstly, the members of the Committee discussed the concept of the cyber-physical manufacturing system enhanced with collective knowledge, and future vision of smart manufacturing (Chapter 2). Secondly, an information model of the cyber-physical manufacturing system useful for examining the machine tool interface was examined (Chapter 3). The Committee suggested use cases for this investigation. The working group then investigated three specific use cases relating to the factory productivity enhancement by using the model (Chapter 4). Finally, by conducting inter-disciplinary analysis for each of the use cases that were analyzed, the common features of the machine interface were summarized (Chapter 5).

(4) Scope

The machine tool interface that is taking an active role of the cyber-physical manufacturing system can be examined in various aspects. This report focuses on the contents of information in the interface. Although the sections relating to installation such as the communication format of the data exchanged by machine tools and the management format are beyond the scope of this investigation, the investigation of machine tool interface was conducted considering possibility of the implementation allowing multiple installations. The investigation examined machine tool interface from the perspective of overall production enhancement of the manufacturing system, and similar investigation can be made for the other components of cyber-physical manufacturing systems as required.

2. Background and vision

(1) Future vision of smart manufacturing

Productivity enhancement of the manufacturing industry is an important issue for building a sustainable society by managing both enhancement of value-added and reduction of environmental impact. Based on this point, machine tool manufacturers have played an essential role for automation of production process and contributed to the productivity enhancement of the manufacturing industry. Machine tool manufacturers will expand their role to manufacturing service providers that provide services based on machine tools as well as supplying machine tools to manufacturers.

The concept of the Internet of Things (IoT) is receiving much attention as a core of the fourth industrial revolution (Industry 4.0). By accumulating and using the information on a variety of facilities that configure a production process including machine tools and robots, the overall production process can be optimized, and therefore, realizing creation of added value over the entire product life cycle.

Smart manufacturing is a typical realization of the IoT in the engineering process. It uses the various information acquired from the manufacturing systems and machine-based intelligence (artificial intelligence) to optimize both production management (supply chain) and production engineering (engineering chain) over the entire product life cycle. The following are the examples of optimizations which can be realized by smart manufacturing:

Visualization of production process: Through the visualization of operating statuses and alarm history of machine tools, information for promoting “on-site improvement activities (Kaizen)” becomes available at the site in real time. This solution enables efficient checking and handling of the issues regarding an entire production line such as line balance and pileup between processes. Furthermore, the scope of visualization expands further to the entire processes of both production management (supply chain) and production engineering (engineering chain) beyond the production line.

Effective utilization of “Kaizen” information: Reflection of the information such as the range of tasks handled by the operator and the process of the operator's awareness attributed to "Kaizen" in the model in the cyber space enables substitution/support for more advanced decision-making processes.

Improvement of quality by inter-process coordination: Product quality can improve comprehensively using the information of each process in a facility such as machining, measurement, and assembly, and by computationally supporting each of these processes.

Bi-directional collaboration between the production management side and the production engineering side: In addition to simply forward information (e.g., production orders) from the production management side to the production engineering side, the production management side could receive frequent feedback of the information (e.g., weather production orders are executed as planned or not) from the production engineering side. This is useful for flexible production planning (e.g., changes of production orders and reassignment of machines).

Securing of manufacturing traceability: A mechanism for reliable communication becomes feasible for notification of frequent design changes in job-order production to various divisions (e.g., procurement, machining, and assembly) of each factory. For the realization of product quality management, the information such as facilities and parts that were used for processing, assembling, and inspection and the information on the operators assigned in each process can be traced from the product.

Enhancement of preventive maintenance, predictive maintenance, and maintenance planning: Signs such as malfunctioning of machine tools can be verified more quickly through the continuous accumulation of factory data and utilization of artificial intelligence. Consequently, production planning and maintenance planning can be optimized in real time in terms of the machine tool life cycle.

(2) Cyber-physical manufacturing system enhanced with collective knowledge

A Cyber Physical System (CPS) refers to a concept of a system that closely coordinates the movements and changes of objects in the real space (physical space) such as materials, machineries, and people and the flow and changes of the information in the cyber space. The system aims at co-evolution of both spaces through bi-directional information flows between both spaces. To achieve this aim, it is necessary to reflect the information that is sensed from the real space to the cyber space quickly and restore the information that has been analyzed and intellectualized to the real space. The concept of considering a manufacturing system as a kind of CPS is recently receiving much attention. In particular, there is a concept of concentrating every piece of information relating to a manufacturing system in the real space into the cyber space, evaluating the status of the system in the cyber space, and providing instructions (feedback) for operation and maintenance of system through the judgment made based on the statuses of the system evaluated in the cyber space. With the increased feasibility of the concept as a result of the progress of various equipment units based on the recent progress of IoT/AI technology, the concept is receiving the support from American and European research communities relating to smart manufacturing.

The mechanisms for performing design, operation, and maintenance of manufacturing systems by using the information in the cyber space following the concept of CPS vary over a wide range according to the overall configuration (architecture) and the value creation system (business model) that encompasses the configuration.

In Europe and America, several implementation mechanisms of smart manufacturing have been proposed. One of the proposed mechanisms is that every piece of information in the physical space (including judgment made by workers) is integrated in the cyber space. It then searches for the global optimum solutions based on the vast volume of information, and as a result production efficiency is enhanced by providing various related services. Another mechanism that has been proposed is that the information that is loaded into the cyber space from devices is combined according to the purpose while recognizing the differences of the sites where the devices are installed, the information is circulated flexibly, and the overall manufacturing system is optimized through the judgment by the local automatic processing and mutual coordination. Either mechanism is based on a hypothesis that information distribution in the manufacturing system model in the cyber space, which has been abstracted with the knowledge and technology currently available in academia and industry, will contribute to realization of the global optimization of the system in the physical space. This is based on another hypothesis that collection of local optimization solutions by accumulation of intentions of workers who are engaged in design, operation, and maintenance of manufacturing systems may not reach the global optimization. However, these mechanisms may fall into inflexible production activities without reflecting the wisdom of on-site workers by placing production sites at the lower stream of the entire information flow starting at the production planning, while such a mechanism contributes to the improvements of the overall judgments based on the integration of the information held by the workers at the various levels who are engaged in the manufacturing system.

In the manufacturing industry in Japan, the mechanism for “Kaizen” has been traditionally practiced, where the machine tool operator of each machine tool of the manufacturing system, line administrators, and production planners provide astute feedback, although locally, while having their own discretion to some extent. This mechanism is based on a historical background where the current manufacturing system in Japan is based on the post-war recovery achieved through the only asset that was remaining, which is people, due to the shortage of technologies and materials. In this mechanism, people make high-level judgment, considering the condition of the production system and surrounding information in a versatile manner and play an essential role in materializing the system. This mechanism is based on hypotheses that the volume of information that can be evaluated on site in the real space exceeds the volume of information that can be reflected in the cyber space and that the on-site judgment made by fully utilizing the difference can be meaningfully utilized for “Kaizen” of the manufacturing system. The mechanism that is practiced in Japan, in which the emphasis is on the local knowledge, regards human as an active component in CPS and produces delicate “Kaizen” performed by human intervention as the starting point. However, at the same time, the mechanism for propagating “Kaizen” across the entire system as information is limited and this limitation may very likely hinder the global optimization.

The mechanism that is being developed in Europe and America, where information on the planning side has the initiative and the traditional Japanese mechanism that emphasizes “Kaizen”, i.e., a set of local judgments with collaborative knowledge, is opposite and at the same time, mutually complementary. Therefore, the ”cyber-physical manufacturing system enhanced with collective knowledge” is considered to be the source of “true Kaizen” for achieving more efficient and intelligent production sites. That is, the bi-directional close coordination between the real space and the cyber space, which is the main objective of CPS, is realized by quickly extracting the wisdom of local production improvements by the discretion of production sites into the cyber space as the critical information, quickly feeding back to the site the wisdom of process improvements for global optimization with computational analysis, and reflecting the wisdom for the local improvements at production sites. As a result, “Circulation of Kaizen” that links both spaces is established, thereby realizing “truly smart” manufacturing.

(3) Importance of machine tool interface standardization

As described before, effective extraction of human judgment in the physical space is an important requirement for the cyber-physical manufacturing system enhanced with collective knowledge, and behaviors of machine tools closely relate to such human judgment. For instance, a machine tool operator dynamically makes fine adjustments of the machining speed considering the state of the tool and, in some case, stops the machine tool operating in automatic mode to prevent any damage to the tool or the work piece. As a result, the machine tool plays a role as a medium (carrier) to inform the result of the human judgment to the production management indirectly.

The interface of machine tools specifies the information that can be obtained from the machine tools and information that is provided to the machine tools. Machine tool designers need to pay attention to machine tool’s capability to retrieve the result of human judgment. Design of the interface without adequate attention leads to the situation that forces unnecessary work on machine tool operators (pressing a button when a specific operation occurs) or forces retrieval of information that is duplicated in other sensors or peripheral devices, causing the unnecessary cost at integration of machine tools in the cyber-physical system.

Machine tool manufacturers have made significant efforts in developing machine tools with the functions that satisfy various requirements. Furthermore, they also develop machine tool peripheral functions for tool changers and operation panels, beyond the scope of machining functions, which is the core, under the fiercely competitive environment. On the other hand, regarding the machine tool model used in the cyber space, mutual compatibility is essential through the interface standardization by abstracting, to some extent, the machine tool features specific to each manufacturer. For instance, in case of replacement of a machine tool with another one with equivalent functions, it is desirable for the machine tool to be able to demonstrate the existing functions without replacing the interface with peripheral devices and software with extended functions like preventive maintenance, predictive maintenance, operation management, and production management. Interface standardization itself does not hinder the competitiveness of the machine tool and the software installed in the machine tool. Interface standardization promotes efficient input of resources of research and development of each machine tool manufacturer to improve the functions of the machine tool itself, which is the source of competitiveness and associated services such as operation management, and maintenance.

Design improvement of each machine tool to enable the person in charge of the production line to produce the optimum result based on the experience is an activity for machine tool manufacturers to attain competitiveness. Extraction of the optimum operating conditions through design of configuration of machines as well as process sequences is a competitive skill of the person in charge of the production line. On the other hand, machine tool manufacturers could cooperate one another for supporting tool users by providing the models of their own tool models for the users to examine the optimum operating conditions also using publicly available information. A mechanism for evaluating whether the conditions are optimum with the machining results may need the standardization of machine tool interfaces. Such a mechanism can belong to the technology in the cooperation area.

Cooperation among machine tool manufacturers is essential for developing standardized machine tool interfaces. Therefore, the attempt to achieve interface standardization by obtaining the cooperation of machine tool manufacturers while incorporating the requests of machine tool users is suitable as the mission of the Industrial Machinery Steering Committee.

(4) In relation to international standard development for smart manufacturing

To implement smart manufacturing by using every piece of information based on the manufacturing system as a cyber-physical system, a mechanism that associates these information pieces and integrates the information as a model is essential. To do so, recently, many proposals for international (e.g., ISO, IEC) standards for smart manufacturing have been discussed. Many of the proposals focus on the abstract framework of manufacturing systems from various scopes (from the device level to the enterprise level). To allow machine tools and their interfaces to play an active role as the core component of smart manufacturing, it is desirable to first focus on nowadays movement of the development of the standards, which are gradually refined. Then manufacturers provide the interface that can communicate with other components of manufacturing systems considering the movement so as to finally demonstrate the full set of the functions of machine tools. For instance, an Industry 4.0 component consists of an object of manufacturing systems and the corresponding Management Shell. Its main function is to connect machine tools and other objects with different interfaces as a means of interface abstraction. It stores the features specific to the corresponding object such as a facility profile. Standardization of machine tool interfaces may result in standardization of their facility profiles, thereby reducing the cost for machine tools to become Industry 4.0 components. Furthermore, there is a possibility for a machine tool to retrieve the information of the surrounding components (processing environment, statuses and alarms of other machine tools, and production plan) via its corresponding Management Shell. By doing so, the machine tool may be able to enhance its performance using wider range of information, and provide the information that assists the judgments of on-site operators.

Application of the existing standard is desirable for the installation of machine tool interfaces such as a communication protocol. For instance, OPC UA is used in the information layer and MTConnect is used in the field layer. As the interface standardization approach relating to "meaning of information" such as data item, a neutral stance is taken for the interface installation options.

Analysis of the interfaces to be standardized and the examination of the methodology towards standardization that were promoted in the activities of this Committee truly play an essential role for implementing the attempt at the site in each country, and it is meaningful for each manufacturer of the machine tool industry in Japan to unite and discuss these issues.

3. Cyber-physical manufacturing system model that visualizes interfaces

(1) Model-based analysis of the cyber-physical manufacturing system configurations

To clarify the configuration requirements of the cyber-physical manufacturing system with collective knowledge, which consists of a variety of components such as workers and machine tools, it is essential to clarify the flow of material and information among these components as well as the consequence of their execution and adjustments. Currently, ERP and various production simulators gather various information on the production plan, material procurement plan, and facility layout into the in-house network. However, the information stored in such systems is not a complete description of the real system: for example, real-time status of the production process progress, adjustment result of the machining process by on-site workers, inventory-level of work-in-progress, exact locations of jigs and tools are often only partially recognized by the computers. Such information should be simultaneoutly accumulated in the cyber space as developed. Rather, on-site workers and administrators are making various production decisions by checking the actual items. In other words, the cyber-physical manufacturing system that helps various decision makings by collecting various information of the actual manufacturing system and uploading them to its representative model in the cyber space in real time has not been realized today. Such a system must be designed and examined while overseeing the future technical evolution.

This report analyzes various aspect of such a future “cyber-physical manufacturing system” by model-based and information-based analysis. We analyze both future requirements for configuration of real-side production systems and future usage of the cyber-side information to achieve robust, flexible, efficient, and value-added production system.

The information model of the cyber-physical manufacturing system describes a series of various actions and judgments that are made in the operation of the production system as the flow of materials and information between the production system components in each use case (for instance, production implementation according to the schedule, maintenance work carried out due to abnormality detection, and adjustment of work contents due to the detection of quality defect). In this model, in principle, a corresponding component in the cyber space is introduced for every physical entity in the manufacturing process. It makes possible to clarify the sequence and frequency of information that is to be exchanged within the production elements in the physical and cyber spaces to improve the efficiency and add high values to the production activities in the physical world by using the cyber space.

(2) Model description rules

The cyber-physical manufacturing system model clearly indicates the components (objects) that form the manufacturing system and the relationship, in particular, of the people, material, and energy (physical operation) among the components, and the flow of related information based on the object-oriented concept, by associating the physical space and the cyber space. Here, the following components in the physical space are specified based on the analysis of the use case explained in Chapter 4. Among these components, which are identified by names, the people and the material in the physical space have characteristics that are classified into work (or workpiece) (rectangle with chipped corners), devices such as machine tools (hexagon), a person or group (ellipse). Re-examination is necessary for this classification method in the course of considering other types of components in the future.

Table 3.1 Example of the components of the cyber-physical manufacturing system model

Name	Basic role	Shape
Work	Target of machining/transportation/quality checking	
Machine Tool	Machine with the work machining function	
Material Handling Machine	Machine with the work transportation function	
Sensor	Element for measuring/checking work status	
Operator	Person who processes work by using a machine tool	
Floor	Group consisting of a production line comprising multiple machine tools and transportation devices and person who controls them. It is not shown in the physical space of the model, because it resembles *Production Control* regarding its role.	
Production Control	Person or group in charge of operation control of the production line	
Quality Control	Person or group in charge of quality control of the work after machining	
Maintenance	Person in charge of maintenance/repair of machine tools	

Next, by describing, as elements, the entire information base relating to the material statuses of all the components in the physical space in the computers and electronic devices in the cyber space as the mirror image of the information in the physical space, the flow of information and judgment is visualized in chronological order between the cyber space and the physical space. By prefixing “D-” (Digital) for the components in the cyber space corresponding to the components in the physical space, the mutual correspondence is clarified. Figure 3.1 shows the correspondence between both spaces in the use case in this report.

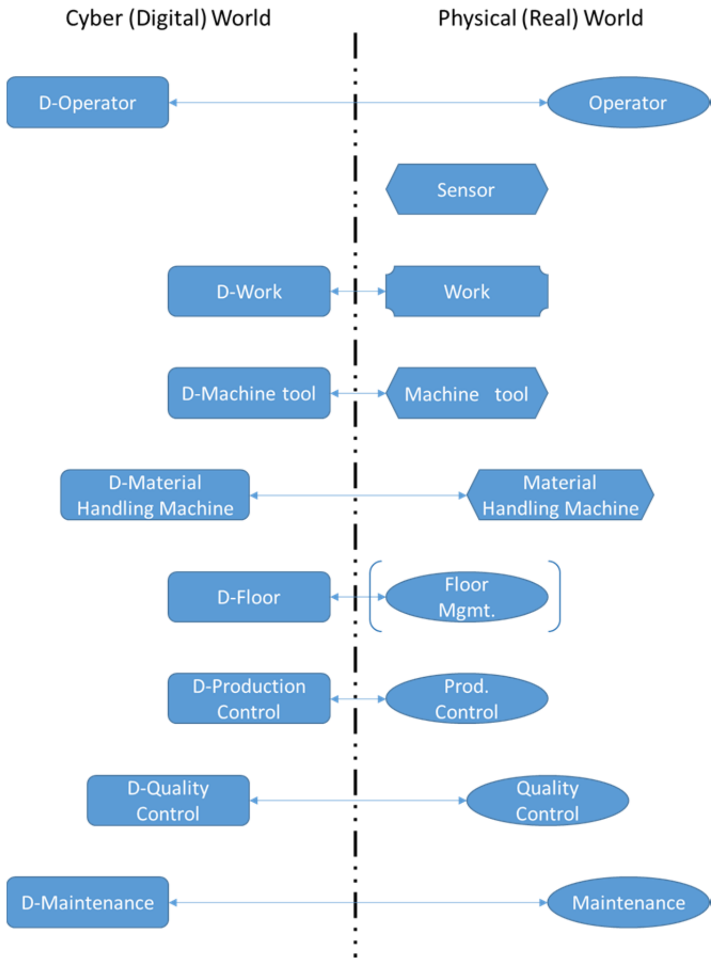

Figure 3.1 Components of the cyber physical manufacturing system model

A state that is considered to be ultimately ideal by the concept of "digital twin" is that the components in the cyber space hold the entire information of the components in the physical space and that all the physical states can be reproduced. However, in the real world, the information of the components in the physical space that can be expressed in the cyber space is limited and the mirror image of the physical space that is produced in the cyber space cannot be a perfect reproduction of the physical world. This gap is essential for this model as long as the physical space cannot be completely predictable.

At the next step, the relationship of interactions between components is extracted in the model and are expressed by arrows in the model diagram. In this model, the inter-component relationships are classified into four categories, information provision/acquisition (for instance, an operator checks the machine condition from the monitor of the machine tool), judgment (for instance, a processor judges the quality of machining work based on the condition of the machine tool), direction (for instance, a production management division directs a machining procedure to the operator), and physical action (for instance, a machine tool processes a work and change the shape of the work).

Elements in the cyber space have three relationships except Action since they cannot directly interfere with the physical world. In particular, the arrow from a component (i.e., source) in the cyber space to another component (i.e., target) indicates that new information on the target component can be acquired by analyzing the information on the component on the source side. For instance, the size of the work after machining can be assumed based on the distance of the axis movement of the machine tool.

The direction of the arrow indicates the flow of information and the direction of the instruction and the number in the figures in the report corresponds to the number in the description in the text.

These inter-component relationships do not clearly indicate the primary information conversion component (that is, the component that converted the information) and the owner of the information. For instance, the entity of the judgment relating to the state of a machine tool can be a server in the cloud or a controller in the machine tool. By applying such a description method, the model can be analyzed by focusing on the contents of the information itself, not the implementation of the information processing.

(3) Model description process

This section shows a simple example that is described in the model mentioned above together with the description process.
For instance, a series of processes of machining work by an operator by using a machine tool are expressed by describing three components, *Operator*, *Work*, and *Machine Tool*, and the relationships sequentially as shown in Figure 3.2.

- *Operator* operates *Machine Tool*. (①)
- *Machine Tool* processes *Work*. (②)
- *Operator* observe the change of the shape of *Work*. (③)

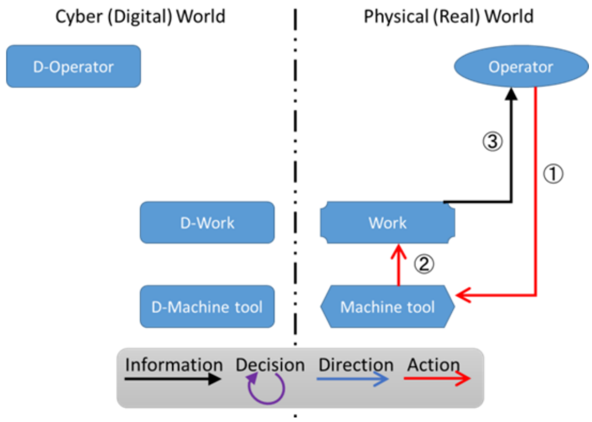

Figure 3.2 Status of machining *Work* by *Operator* by using *Machine Tool*

As described above, ideal components corresponding to *Operator*, *Work*, and *Machine Tool* are instantiated in the cyber space. These components in the cyber space have all the information of the corresponding components, for instance, in case of *Work*, the shape, surface roughness, material properties, position, and posture, and the conditions change according to the change of the conditions of the corresponding component belong to the attributes of *Work*.

Then, let us examine a specific process for achieving high efficiency and high value-added in the production process. Initially, based on the assumption that there are ideal components with the characteristics mentioned above in the cyber space, an action, information flow, direction, and judgment that form the proposed process are described. For instance, Figure 3.3 shows the process for adjusting the behaviors of *Machine Tool* (for minimization of energy consumption, giving consideration to the habits and material properties) based on the information on *Operator* (operation habits) and *Work* (material properties) in the condition shown in Figure 3.2. In Figure 3.2, the information about *Operator*, *Work*, and *Machine tool* in the physical space is transferred to each component in the cyber space (④), parameters of *Machine Tool* suitable for *Work* and *Operator* are specified (⑤), and the parameters are fed back to the operation of *Machine Tool* (⑥). This reduces the adjustments of *Machine Tool* required by *Operator* and enables fine adjustments according to the material property of *Work*, which *Operator* was not previously aware of. This contributes to the improvement of quality and yield, and more flexible and quick machining process for various types of works.

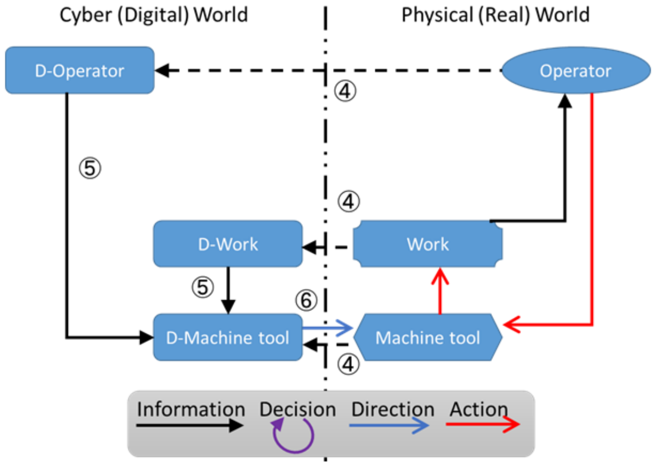

Figure 3.3 Behavior adjustments of a machine tool in the ideal condition

Figure 3.3 shows the result of the discussion based on the assumption that the entire information on components of the physical production system is copied on to the corresponding components in the cyber space without delay. However, this does not always happen in the real world. For instance, some work carries just an extrinsic function (e.g., to fasten parts) or it is a mass-produced part in lot units. Thus, it is not realistic to assume that the individual work is identifiable and possess its own state (e.g., being processes) in the real space, and the information is reflected in the corresponding elements in the cyber space. In reality, rather, it is natural for the state of the work to be measured by an external testing device. It is not easy to acquire the information such as the position of the operator, work contents, health condition, and intention (what the operator intends to do next) and position judgment by photographing with a wide-area camera, patterning of work history of the operator, and retrieval of the operation history from the machine tool are necessary. Figure 3.4 shows an example of automatic adjustment of *Machine Tool* in the ideal condition shown in Figure 3.3 based on the realistic means for information acquisition and transfer. Specifically, information on *Work* and *Operator* can be assumed from the flow of information such as acquisition of own information from *Machine Tool* (⑦), analogical reasoning of the information on *Operator* and *Work* from the information of *Machine Tool* (⑧, ⑨), and acquisition of the information of *Work* by using *Sensor* (⑩).

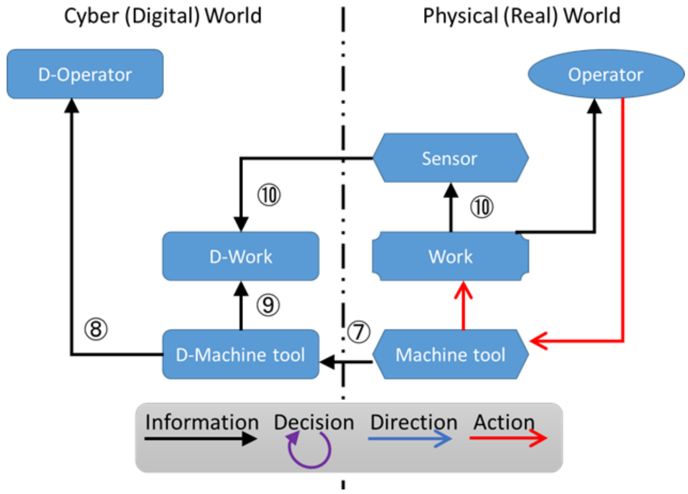

Figure 3.4 Automatic adjustments of *Machine Tool* in a realistic condition

(4) Features of the model

The cyber-physical manufacturing system model was developed based on the assumption that components corresponding to those in the physical space exist in the cyber space. The features of the model that is derived from this assumption are classified based on the three aspects, similarity, time evolution, and feedback, and these features do not depend on specific use cases.

Similarity of the manufacturing systems in the physical space and the cyber space: The manufacturing system in the cyber space has the information that expresses the ideal state "to be" when unmistakably viewed as information processing-based. On the other hand, the manufacturing system in the physical space comprises the elements of production activity implementation and the elements that bear production activities such as facilities of the system that constructs the current state ("as is") of the production site and the measuring equipment for acquiring and maintaining the state. The state "to be" is constructed by abstracting the functions of information processing from the manufacturing system in the physical space and it is modelled with the assumption that all the elements that exist in the physical space also exist in the cyber space. Since, in general, the conditions relating to information transfer and processing differ between the cyber space and the physical space, the component configuration in the cyber space does not necessarily match the component configuration in the physical space. For instance, it is not necessarily reasonable to express, in the physical space, the action of pressing a button of a machine tool by an operator in the physical space with two separate components such as an operator and a machine tool. Similarity is required for the cyber space and the physical space only to construct a primary model to abstract the functions of the manufacturing system in the physical space and, after considering the characteristics distinctive to the cyber space, the component configuration in the cyber space is changed to the component configuration different from that in the physical space as required.

Time evolution of the manufacturing system in the physical space and in the cyber space: The time evolution of the manufacturing system in the cyber space that is constructed corresponding to the system in the physical space is calculated and predicted as required by using a simulator. The state of the system in the physical space is controlled so that the it matches the state of the system in the cyber space. When the operating status of the production line assumed in the cyber space does not match the on-site status any longer, a measurement is taken, that is, either changing the model in the cyber space or changing the status at the site. In the former case, the precision of the production model in the cyber space is enhanced and in the latter case, improvements are made so that the operating status more closely resembles the production plan.

Feedback of the information relating to the manufacturing system from the cyber space to the physical space (i.e., real world): If the state of the manufacturing system in the cyber space differs from that of real world, an alarm is issued in the real world and various instructions are sent to the system to modify the state of the real world (feedback). The levels of this feedback vary. For instance, in some case, the machine tool operator detects the abnormality of the machine (e.g., strange noise) and adjusts the behavior of the machine tool (e.g., override). In other case, due to the inoperative state of the machine tool, a critical alarm is issued, forcing the modification of the production plan and a machining instruction is issued to other machine tools through MES. In general, as the degree of diversion of the states of the production system of both worlds increase, the feedback loop that is required for modification expands, thereby increasing the time required for the modification.

4. The use cases for improving smart factory productivity in multiple phases

This section provides use case analysis using a cyber-physical manufacturing system model described in the previous chapter. We regard “improving productivity of manufacturing systems” as the main theme of use cases, considering suggestions of the members of the Committee who have been involved in management planning for the overall production system and production lines and on-site improvement activities (“Kaizen”) and also the opinions of users of their machine tools. This chapter introduces three use cases: “operation tracking and global optimization”, ”quality control”, and "repair, preventive maintenance, predictive maintenance", which lead to improvement of productivity.

This use case analysis covers not only capability of current machine tools but also next generation machine tools, peripherals, robots, and production control systems that are likely to be implemented by 2025. With this framework, roles of the current and next generation machine tools and peripheral components for the use case purposes in the cyber-physical production systems are analyzed, where manufacturing system workers' decision is utilized. The model described in the previous chapter is used to analyze actions, the flow of instructions, and assessment of situation between machine tools and peripherals

(1) Operation tracking and global optimization (use case 1)

Understanding the operating progress of production lines by using real-time operating data is effective for reviewing production/maintenance plans and facilitating use of idle equipment. For example, it is possible to make a plan to level loads on machine tools based on the acquired load data for the entire plant. To improve the accuracy of production line operation tracking, various data regarding machine tools, peripherals such as transport devices and robots, and data from production line workers are essential.

Poduction plan is scheduled normally a weekly or monthly basis, but it should be reviewed as required if it is urgent. Only experienced on-site workers can adjust the plan, because it is required to analyze on-site phenomena and make judgments by themselves to adjust the processing speed or change the order of processing depending on the quantity of workpieces to be processed. This adjustment may not be reflected in the production history and not lead to global optimization because measurements are dependent on skills and experience of on-site workers. For example, if there is enough time before transport, workers do not need to accelerate on-site work but rather need to prioritize other tasks while waiting for the next workpiece. However, on-site workers are usually assigned only a task of executing a part of the entire production plan, and it may not be expected or allowed for the workers to do the above adjustment influencing on the entire production plan.

To improve productivity in a cyber space while preventing local optimization dependent on on-site workers' judgments and detecting deviation from the plan, the following technical development is necessary.

- More frequent monitoring of production line operating status
- Formalizing knowledge and judgment regarding production line operating procedures
- Methods to record on-site judgment without increasing burdens on workers

a. Current status of production line operation monitoring and control (Figure 4.1)

Currently, progress of operations is controlled through comparison and modification between work plans and work results. Figure 4.1 shows the current status of operation monitoring and control using a model suggested in Chapter 3. The numbers from ① to ⑥ below correspond to the numbers in Figure 4.1.

First, *Production Control* creates an instruction (*D-Floor*) for the floor (i.e., a production line)(①). This information is then directed to *Operator* and *Material Handling Machine* (②). *Material Handling Machine* delivers *Work* to *Machine Tool* (③), and *Operator* uses *Machine Tool* to process *Work*. The results of machining process on *Work* are updated via *Machine Tool* (④). This information is compared and analyzed with the plan on *Production Control* (⑤). A skilled worker, if present, will go and get *Work* (i.e., a workpiece) if it cannot be delivered due to a problem with *Material Handling Machine* (⑥). As such, on-site workers can make adjustment to a certain degree.

Table 4.1 shows the information that *Machine Tool* should provide to the cyber space at step ④. *Machine Tool* currently does not have *Work* position information, and thus it needs to retrieve it from *Material Handling Machine* or *Operator* needs to read it manually with, e.g., a bar-code reader.

The problem here is that on-site adjustment inevitably leads to localized optimization, and the progress will be delayed because variance between the plan and result needs to be addressed.

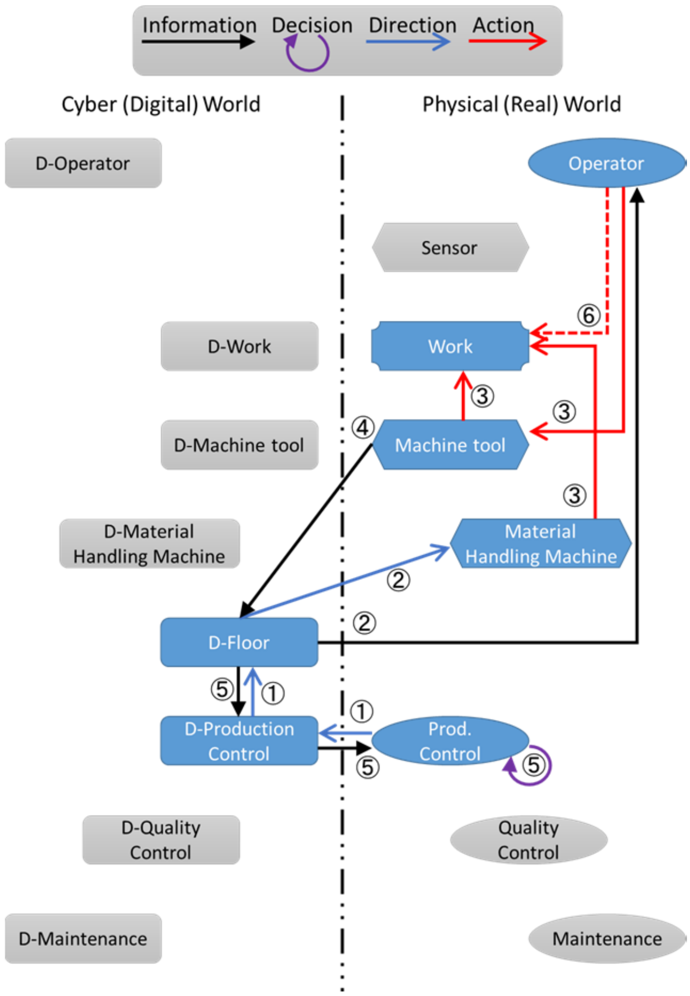

Figure 4.1 Current status of production line operation monitoring and control

Table 4.1 Information for production line operation tracking (current status)

Component name	Item	Remarks
Machine	Machining result	Variance between the plan and result is measured every second.
Machine	Operating result	Basic information to determine the production line status (processing/stopped/alarm) is measured every second.
Machine	Alarm information	This information details an issued alarm. It is created when an alarm is issued.
Machine	Equipment information	This profile is used to analyze alarms and machine status.
Machine	Program number	Data indicated by numbers on the chart is measured every second to determine the processing status.
Material Handling Machine	Position, workpiece number	This data (station number, transit point, etc.) is measured every second to track the workpiece position.

b. Future image of production line operation monitoring and control (Figure 4.2)

By 2025, the Japanese manufacturing industry will have accumulated knowledge of measures created and applied on-site by skilled workers to the level of “production plan model changer” in the cyber space, and this enables integration of various patterns of local optimization to enhance their knowledge. (The detail of “production plan model changer” will be described later in this section.) This model changer can support sharing of local optimization patterns with every site or plant, and then it will be utilized in the entire industry to enable global optimization.

The following describes the processes of global optimization using the "production plan model changer". Figure 4.2 shows the flow of operation monitoring and control using a model described in Chapter 3. The numbers from ① to ⑮ below correspond to the numbers in Figure 4.2.

1) Creating a production plan: The initial state of production plan (*D-Floor*) is created in the cyber space based on the order information, capacity information of the plant or affiliated plant (①), converted to instructions on *Work* and notified to *Material Handling Machine* and *Operator* (②). The same information is sent to *Machine Tool* and *Work* is machined as instructed when it is delivered to *Machine Tool* (mainly processed automatically but handled by *Operator* as needed) (③).
2) Aggregation of production result and detection/visualization of faults:

Machine Tool uploads the result of machining to the cyber space (④). The machining result on the floor along with information retained in *Material Handling Machine* are aggregated (⑤). Nonstandard operations done by *Operator* by self judgment are detected (⑥), which can be extracted from video images integrated with the production result (⑦). With this mechanism, on-site activities done by *Operator* such as quick resolving of waste of overproduction can be reflected in the cyber space (⑧).

3) Automated correction of variance between the plan and result: The production plan and result are compared (⑪), and the plan is corrected by Scheduler to eliminate the variance (⑫), and the corrected plan is applied (⑬). If the variance is too large and the model (e.g., operational flow type) needs to be changed for the plan (⑭), a simulator or similar equipment is used to predict future problems from production result and correct the model (⑮).

Table 4.2 lists the items related to the state of production (colored, also listed in Table 4.1) and of *Machine Tool* (maintenance timing, etc.) which affects the production plan. Such information needs to be regularly uploaded to the cyber space. This kind of information may need to be handled explicitly by a simulator or model of the production plan. In addition, it is suggested that workers' know-how that was previously used only on-site should be shared. Such local information should be explicitly represented in a production model to effectively analyze which part of it can be utilized for global optimization.

This conceptual model has processes of providing feedback from on-site improvement activities to the cyber space and improving the manufacturing system itself. In other words, “Kaizen” for production models in the cyber space is achieved through “Kaizen” on-site. As the model can detect the variance between given rules and its actual behavior, if they are modeled in an appropriate manner, it can also be used to decrease risks regarding the compliance with these rules.

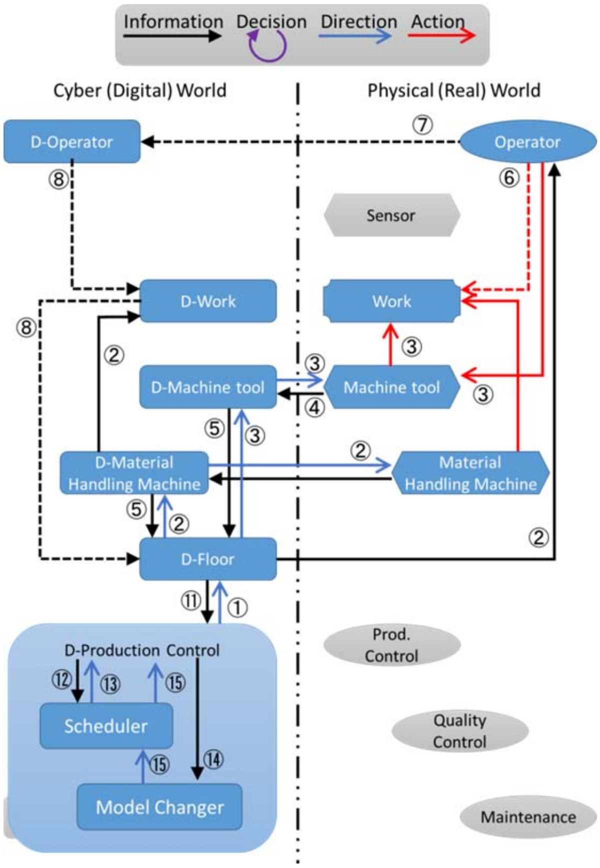

Figure 4.2 Future image of production line operation tracking and management

Table 4.2 Information exchanged for production line operation tracking

Component name	Item	Remarks
Machine	Machining result	Variance between the plan and result is measured every second.
Machine	Operating result	Basic information to determine the production line status (processing/stopped/alarm) is measured every second.
Machine	Alarm information	This information details an issued alarm. It is created when an alarm is issued.
Machine	Equipment information	This profile is used to analyze alarms and machine status.
Machine	Program number	0 number. Data indicated by numbers on the chart is measured every second to determine the processing status.
Material Handling Machine	Position	This data (station number, transit point, etc.) is measured every second to track the workpiece position.
Operator	Position	Track the operator's position every second to detect any behavior that is irrelevant to the procedure.
Operator	Work memos, pictures	Record on-site solutions.
Machine	Maintenance forecast	Notify of a date on which maintenance become required.

(2) Quality control (use case 2)

In future quality control, possible incidents occurred to in plants, production lines, machines, workpieces, and jigs/tools need to be predicted, and measures against such incidents should be taken for stable and enhanced quality and production control. This section discusses information that should be retained in each element of the model, the flow of actions, directions, and information between elements based on the model for the cyber-physical production system described in the previous chapter.

The model described in the previous chapter is used for analysis of an error handling in machining. This model indicates processes of notifying the production control of information regarding machining failure, proceeding with or termination of machining processes, handling defective products, and modifying the production plan.

a. Current status (Figure 4.3)

Major decisions in *Quality Control* and *Production Control* such as regarding how parts machining quality affect finished products, or at which phase a process of the line should be stopped are made by each operator after discussing with related divisions (e.g., a quality control devision). Currently, there is no such elements in the cyber space. Therefore, the current model of the cyber-physical manufacturing system only defines the flow of actions and information exchanged between components as shown in Figure 4.3.

Work after machining is measured by *Sensor* for evaluating quality (or testing instrument) (①). *Operator* reads the inspection result shown on the sensor (②), and evaluate the quality (③). If *Operator* judges the quality to be insufficient (④), *Operator* reports the result to *Quality Control*, in which whether the quality problem is caused by the process itself or a purchased item is evaluated (⑤). If the process is faulty, *Quality Control* influences the content of *Production Control* to make decision on termination or modification of the process (⑥). When such a judgment based on the information about *Production Control* is made (⑦), it directs *Operator* involved in the process and related processes to terminate or modify the process (⑧). Then the Operator operates the *Machine Tool* as directed (⑨).

Table 4.3 organizes information referenced in this process.

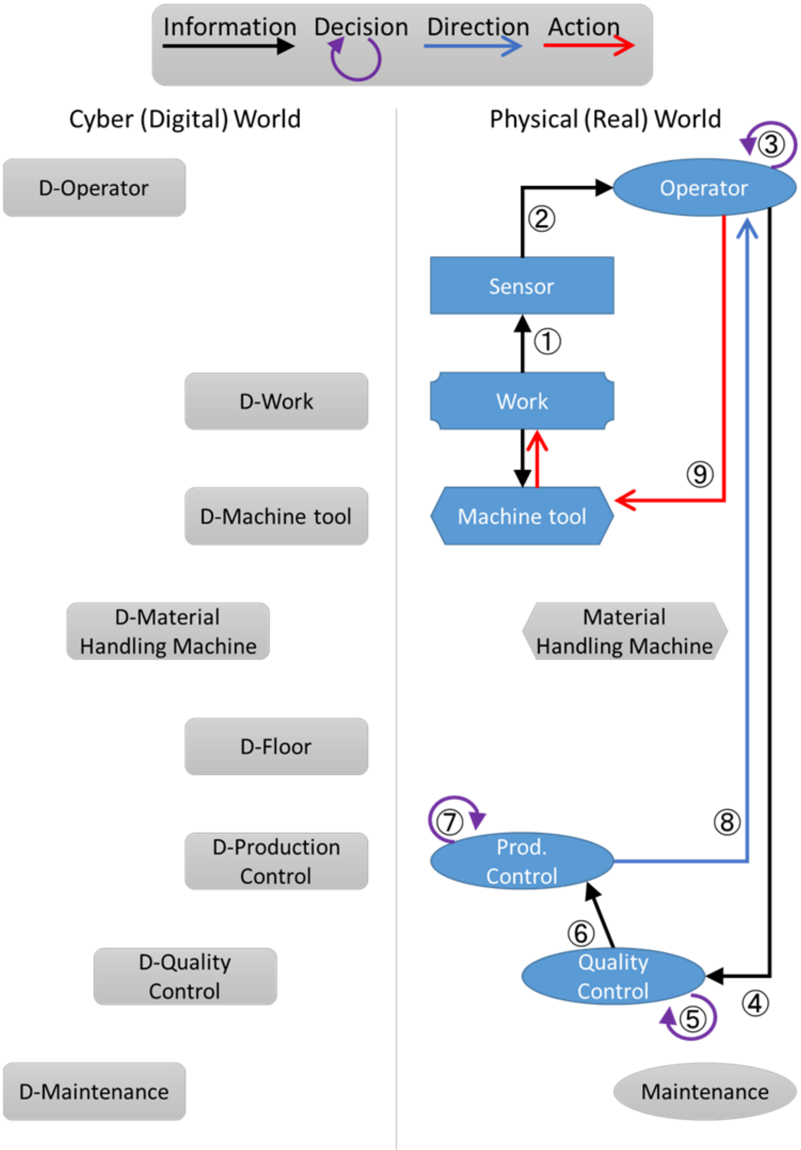

Figure 4.3 Current status of the quality control process

Table 4.3 Main information used by the current quality control process

Component name	Item	Remarks
Sensor	Measured values	Quality-related information such as dimensions and surface roughness acquired per work piece
Machine Tool	Controller information	Status, alarm, warning, etc.
Operator	Measured values, machine status, machining status	Quality-related information for operators
Operator	Machine status	Machine status inferred by the operator from noise or vibration. This status is not real-time data since the operator takes time to determine the status.
Operator	Machining status	Machining status inferred by the operator from noise, vibration, or colors. This status is not real-time data since the operator takes time to determine the status.
Operator	Machine information	Information such as spindle load inferred by the operator based on his knowledge. This status is not real-time data since the operator takes time to determine the status.
Quality Control	Alarm/warning	Information of occurrence or sign of defective products
Production Control	Alarm/warning	Information of abort or modification of work
Machine Tool	Command	Command information received by the machine tool, such as input to the control board or NC program change
Work	Tacit knowledge	Experienced operators' knowledge regarding shape- or material-dependent behavior of the workpiece being processed
Machine Tool	Tacit knowledge	Experienced operators' knowledge regarding machine behavior related to machining behavior and tool status
Operator	Tacit knowledge	Experienced operators' knowledge regarding setup and conditions to finish work.
Quality Control	Tacit knowledge	Experienced quality controllers' knowledge regarding quality tracking, process tracking, and trends found in the tracking.
Production Control	Tacit knowledge	Experienced production controllers' knowledge regarding process relation, inventory of goods in process, lead time history, delivery dates, and productivity.

b. Future quality control (Figure 4.4)

This section describes a quality control model in the future following the cyber-physical system modeling described in Chapter 3. The followings are tips for creating a cyber-physical manufacturing model for quality control.

(1) Components in the cyber space should correspond to those in the physical space.
(2) Skills in workplace should be represented in this cyber-physical manufacturing model. In particular, transcribe physical-space components and workers to the cyber space, clarify foundation or reasoning for determination/decision and other information, and properly abstract and associate them to components transcribed to the cyber space. As a result, knowledge of on-site workers and quality controllers are transcribed to the cyber space.
(3) The manufacturing system model should consists of various cyber-space components/workers capable of making decision autonomously based on highly accurate local information instead of using top-down approach. Alarms and other information issued autonomously by components will become a starting point of a series of quality control processes. Components in both physical and cyber spaces should become the starting points of a variety of alarms.
(4) Theoretically, all the components in the cyber space have a model (behavior model for itself) to predict the behavior of the corresponding component in the physical space.
(5) Not only machine tools and other devices, but also workers and quality controllers in the physical space are regarded as components in the cyber space. Therefore, a mechanism enabling these components to learn determination/decision making should be implemented.

Based on the above points, Figure 4.4 shows a cyber-physical manufacturing system model for quality control in the year 2025.

D-Machine Tool notifies *D-Work* of the necessary procedure for processing (①). At the same time, *D-Machine tool* operates itself in the physical space (i.e., *Machine Tool*) to process *Work* (②). *D-Work* is notified of *Work* processing status read by *Sensor* (or other testing instrument) (③). *D-Work* compares its status estimated from the machining procedure at step ① with the status of *Work* in the physical space at step ③, and evaluates its quality based on the variance between them (④). If *D-Work* evaluates that the quality may be insufficient, *D-Work* notifies *D-Quality Control* of this possibility (⑤). *D-Quality Control* estimates the cause of insufficient quality (process itself or a purchased item) (⑥), and notifies *D-Production Control* of this estimation (⑦). *D-Production Control* evaluates whether the process or related processes should be terminated or modified (⑧). To do so, instructions are given to relevant machine tools via *D-Floor* (⑨). As a result, *D-Machine Tool* directs *Machine Tool* to terminate its operation or modify its processing procedure.

In this model, it is assumed that *D-Machine Tool* autonomously creates processing procedure, performs setup, and adjust processing parameters. Therefore, note that *Operator* who makes decision on processing and process designing in Figure 4.3 will be no longer liable for such decision making. The knowledge of *Operator* regarding process designing and setup is formalized and learned by *D-Machine*. This can be tacit knowledge. In this case, the changeover order or timing and hidden intention of these actions can be inferred and leaned from operators' handling of workpieces and tracking of operators movements (⑪). The same applies to *D-Quality Control* and *D-Production Control*, which correspond to quality control and production control in the physical space. By learning decision making processes from highly experienced quality controllers and production controllers (⑫, ⑬), a cyber-physical manufacturing model integrating workplace skills will be created.

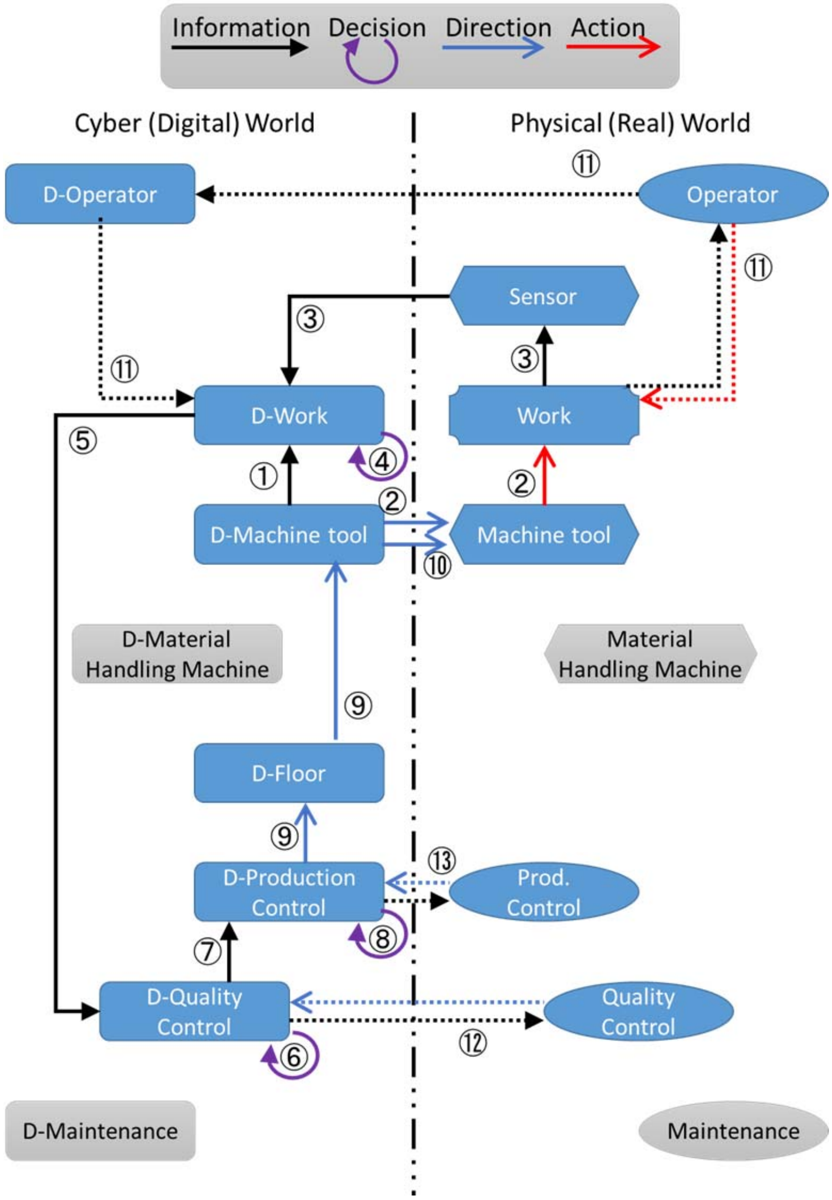

Figure 4.4 Future quality control process

Table 4.4 Main information used for future quality control process

Component name	Item	Remarks
D-Work	Shape	Information regarding the original and finished shapes of workpiece acquired when starting processing.
D-Work	Setup status	Information regarding how the machine and peripherals (tools and jigs) are handled by the operator (③)
D-Work	Machine information	Position information (①)
Sensor	Measured values	Various information such as dimensions and surface roughness of the workpiece acquired from sensors and testing instruments (③)
D-Work	Variance from the normal state	Information regarding variance from the normal range predicted by a behavior model. Possibility of defective products is considered. Currently, recognition and decision depends on *Operator* (⑤).
D-Quality Control	Variance from the normal state	Information used to recognize variance from the specified quality. Currently, recognition and decision depends on the Operator (⑥).
D-Production Control	Variance from the normal state	Information used to recognize the fact that processing/assembly is not on the specified production schedule. Currently, recognition and decision depends on Operator (⑧).
D-Production	Emergency decision	Information used to modify the production plan in emergency situations (⑨)
D-Machine	Emergency decision	Information regarding instructions (e.g. continue, stop, or redo steps of workpiece processing) given to machine tools in emergency situations (⑬).
D-Sensor	Error	Error occurrence rate and reliability based on the measurement principles (③)
D-Operator	Formalized tacit knowledge	Information that should be retrieved by an agent that handles the knowledge of *Operator*
D-Quality Control	Formalized tacit knowledge	Information that should be retrieved by an agent that handles the knowledge about *Quality Control*
D-Production Control	Formalized tacit knowledge	Information that should be retrieved by an agent that handles the knowledge about *Production Control*

(3) Repair, preventive maintenance, predictive maintenance (use case 3)

Machine tools in plants do not always operate without fault. A machine tool normally stops due to failed processing, lack of consumables and supplies, random failure and other reasons, and this significantly affects production plans and results. To increase the overall productivity of the plant, not only improving the normal state throughput, but also minimization of the effect of such faults is important. Currently repair and maintenance tasks are performed in certain fixed intervals mainly based on tacit knowledge of line operators in order to minimize possibility of random failure. However, to reduce the random failure rate effectively, premature or precautious scheduling of the maintenance is required, which decreases the overall performance. In future, it would be possible to prevent potential failure by detecting signs of equipment failure, changing production plans, decreasing the load on the to-be-failing equipment. By taming occurrence of such potential failure, and by coordinate the planed scheduling of early maintenance coordinated with those of other equipments, the operating rate and production rate of overall plant can be improved even with the same operating rate of each equipment.

This section analyzes necessary information at three phases i.e., normal operation, deterioration (partial malfunction of equipments), and failure phases to discuss methods to enable more efficient line operation.

a. Normal operating state (Figure 4.5)

In the normal operating state, *D-Machine Tool* collects information from various data sources to evaluate its integrity. In addition to status information of the actual machine tools itself, the processing result of workpiece, caused by various phenomena of the machine tools such as rough grinding can also be used to find to determine the machine integrity (①). *D-Machine Tool* continuously evaluates its integrity based on this kind of information (②).

Each equipment will have its own trends of deterioration specific to each various local aspects such the target workpieces, production location, or the manufacturer. Also, it may have trends which are unique to the set or lot of machine tools, not specific to a single manufacturer. To utilize such non-local trends, the machine tool manufacturer may share information in the *D-Machine Tool* (③) with each plant, and gather data from multiple machines of the same model from various locations to *D-Machine Tool Model* (④) for analysis. The analysis result will be shared back to the plant to support decision making in the plant. There are possible several implementation methods for this model. One example is to implement *D-Machine Tool* within the plant and to exchange the minimal trend data with the machine tool manufacturer. Alternatively, the tool manufacturer may provide all functions of the plant-side *D-Machine Tool* via a cloud networking, and use trend analysis to assist decision making in the plant. The possible method varies depending on the data quality, costs, and confidentiality of the processing.

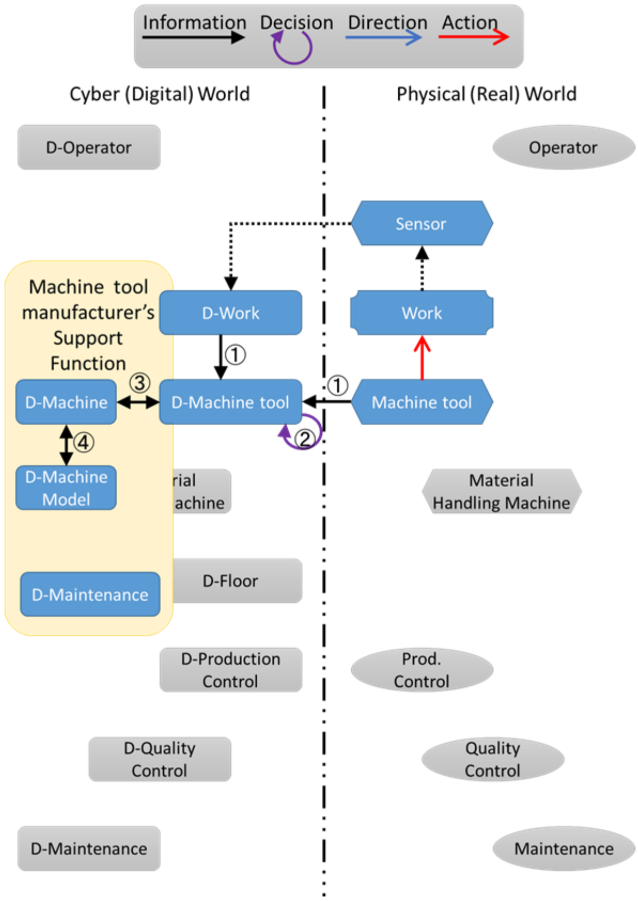

Figure 4.5 Normal operating state

b. Rescheduling the production plan due to functional deterioration and preparing maintenance (Figure 4.6)

If *D-Machine Tool* determines that functional deterioration or failure is likely to occur, the cycle of the information becomes larger than the normal state in order to review the production plan and prepare maintenance considering the effect on production.

If *D-Machine Tool* determines that it cannot or will not be able to provide expected performance for the production plan sooner or later, the relevant alarm is issued to *D-Floor* (③). *D-Floor* analyzes its impact to the current line processing status, and if the status is faulty, it issues alarm to the upper-level *D-Production Control*. At the same time, this information is shared with *Machine Tool Manufacturer* (③-b). *Machine Tool Manufacturer* prepares information required for planning of future repair, based on trends and other information shared in the normal state (③-c).

D-Production Control also determines the impact of the trouble state to the current production plan (⑤). It also asks information from *Machine Tool Manufacturer* for the delivery of repair parts etc (⑥). Based on these information, *D-Production Control* and the real human *Production Control* determines the best plan for contingency (⑦), such as changing processing method for reduction of the load on the faulty machine, avoiding faulty equipment by changing the production plan, or scheduling early maintenance of other equipment to minimize the stop-time of the whole plant. When the decision is made, *D-Floor* (⑧) and *D-Machine Tool* (⑨) are notified of the new plan, and reflected to the real production actions (e.g., reduction of processing speed, avoiding faulty sections, etc.).

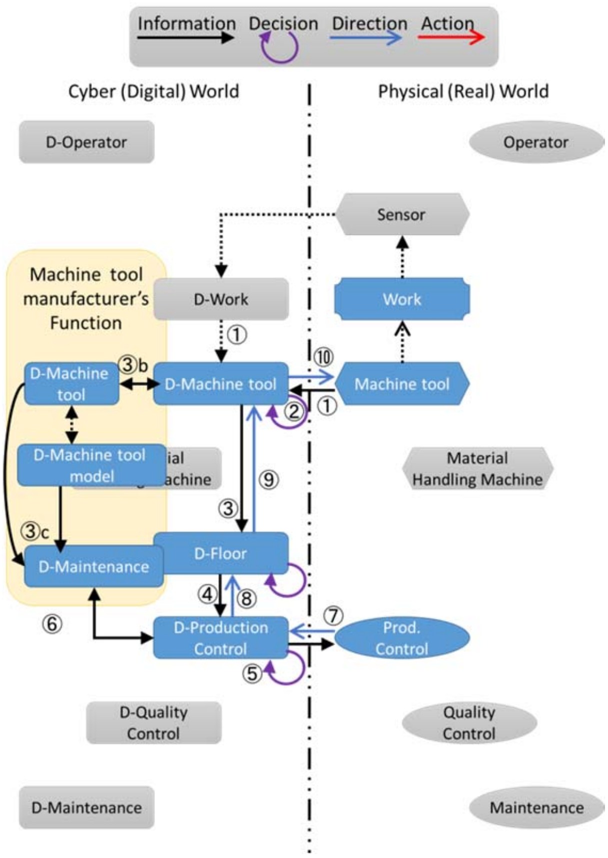

Figure 4.6 Production plan adjustment due to functional deterioration

c. Handling failure (Figure 4.7)

If actual equipment is to be repaired after the above temporary measures are applied, the production plan is adjusted and a maintenance instruction for relevant equipment is issued from the *Production Control* and then *D-Production Control* (①, ②). Based on this instruction, *D-Machine Tool* directs the real *Machine Tool* to terminate its operation (③, ④). At the same time, *D-Maintenance* is directed to start maintenance (⑤), and *Machine Tool Manufacturer* is requested for supplying repair parts and for support for the maintenance, based on the previously–shared information on *Machine Tool* (⑥).

The real-world *Maintenance* sections receives the information of the failure from the from the cyber space (⑦), and perform the real action to *Machine Tool* (⑧), possible with a support from the *Machine Tool Manufacturer*'s support team as needed (⑦-b).

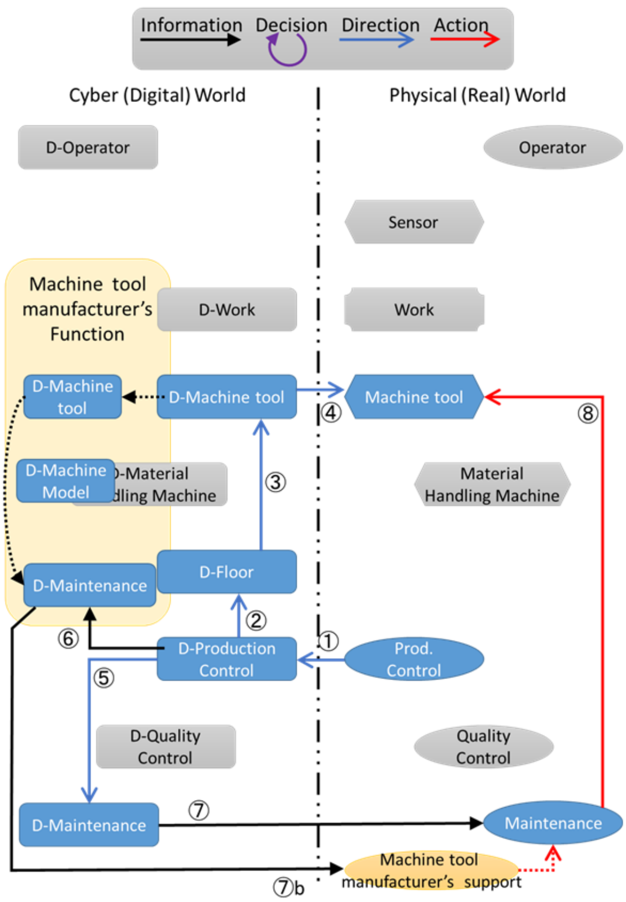

Figure 4.7 Handling failure

Table 4.5 Information used in the normal state, degraded state, and failure state

Component name	Item	Remarks
1. Monitoring in the normal operating state (Figure 4.5)		
Machine	Operating status	Running, stopped, etc.
Machine	Processing information	NC program name, sequence number, etc.
Machine	Physical behavior information	Information of each axis such as the current position, speed, load, temperature, and power
Machine	Unit information	Usage frequency of relays, switches, magnets, capacitors, etc.
Machine	Functional deterioration information	Servo axis information (current/deviation) [%, mm], vibration of each unit, sound, temperature (motors, ball screws), tool wear level, etc.
D-Work	Processing result information	Workpiece dimensional accuracy, etc. Real-time data will be available by 2025.
D-Machine	Diagnostic information	Information sharing between the user and Machine Tool Manufacturer and trend data sharing between devices (③, ④)
2. Degraded operation due to functional deterioration, adjustment of production plan, and preparation of maintenance (Figure 4.6)		
Machine	Alarm information	Figure 4.6 ①
D-Machine	Fault information	③
D-Machine (Operator)	Determination result	Result determined using thresholds that are manually set
D-Machine	Prediction of deterioration	Details of functional deterioration or time of expected functional halt (③)
D-Floor	Prediction of production delay	Prediction of a production plan not to be achieved (④)
D-ProductionControl *D-Maintenance*	Adjustment of maintenance schedule	Delivery date of repair parts, support schedule using the information available on *Machine Tool Manufacturer* side (⑥)
Machine Tool *D-Machine/* *D-Machine Model*	Machine characteristics	Equipment characteristics and maintenance information available on the *Machine Tool Manufacturer* side (③-c)
D-Production Control	Rescheduling of production plan	Rescheduling of the production plan to minimize the effect on the delivery date (⑧)
D-Floor	Rescheduling of machining plan	Rescheduling of the machining plan due to the change of production plan (⑨)
D-Machine Tool	Instruction for degraded operation	Instruction to decrease the processing speed to continue production (⑩)
3. Handling failure (Figure 4.7)		
D-Production Control	Instruction to terminate production	From ① to ④
D-Production Control (or D-Floor)	Instruction/request to start maintenance	Procurement of parts for maintenance, arrangement for work (⑤, ⑥)
D-Machine	Fault information	(via *D-Production Control* and *D-Maintenance* in Figure 4.6) Information sent when function deterioration occurs needs to be shared to perform actual maintenance.

5. Analysis of the machine tool interface enhanced with collective knowledge

In Chapter 4, three use cases were presented for the cyber-physical manufacturing system enhanced with collective knowledge, so that the actions of manufacturing system components, information flows between the components, and directions and judgments influencing the state of components and the corresponding models made clear. As various use cases have to be taken into account in design, operation and maintenance of manufacturing systems, it will be useful to integrate models created through analysis of multiple use cases and to analyze the characteristics of those models.

Figure 5.1 shows a manufacturing system model created by integrating three use cases. The next paragraphs summarize the findings from the analysis of the figure and the use cases.

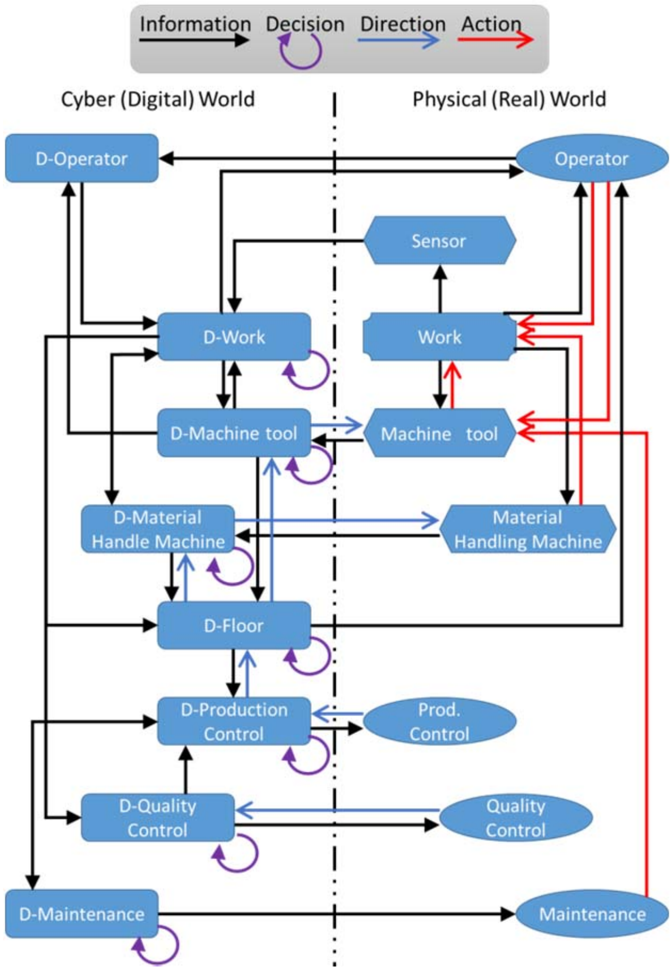

Figure 5.1 Integration of manufacturing system models for use cases

(1) Examinations of use case analysis results

Information about *Work* plays an important role in various use cases of the model. In the use cases it was assumed that *Work* did not have an ability to transmit its own information (such as its ingredient characteristics and quality) to the cyber space by itself (i.e., there are no lines directly connecting *Work* and *D-Work*). Despite that, information about *Work* obtained through various components, including sensors, machine tools, material handling machines or operators' actions, was supposed to be used at all levels of judgments and directions in the operation management, quality control, maintenance and other processes of the manufacturing system.

Information flows between components in the cyber space represent the information dependence of each component. The left half of Figure 5.1 shows *D-Machine Tool* is directly linked with *D-Work*, *D-Operator* and *D-Floor*, resembling the operator environment at production lines of factories in the real space. That indicates future use cases now being considered can basically be deemed as an improved version of the current production environment. Meanwhile, traditionally, production line administrators coordinate operations of machines and tools in factories. But as operations of various machines and tools are automated and far-sighted production control functions are introduced, the line administrator is just required to manage each line separately and the administrator role is absorbed into *D-Production Control* in the model. Those changes deviating from the conventional production environment could be identified in the future as more dynamic structural changes in the information flows if considering more innovative use cases.

In the use cases, alarms are regarded as information essential to start decision-making and countermeasures when the behavior of manufacturing system components deviate from normal conditions. The information that starts from the alarm of *Machine Tool* is processed through various decisions before reaching *D-Production Control*, so new meanings will be added. This means there are two types of alarms in terms of their meaning and significance: ones that allow the starting point (primarily *Machine Tool*) to decide how to handle the situation only based on its own information; and those for which countermeasures can be decided by *D-Floor* and *D-Production Control* only after the production plan and other surrounding circumstances are comprehensively examined. Those different types of alarms suggest the necessity of categorizing signs of abnormalities that could occur at various levels in integrated cyber-physical manufacturing systems based on whether the abnormalities are serious or not, so that they can be transmitted to sections that need them. If viewed from a different perspective, the model shows not only information associated with *D-Machine Tool* but also part of information belonging to *D-Floor* and *D-Production Control* or more specifically information on surrounding circumstances, the production plan and quality requirements for processed goods–may need to be provided to machine tools, so machine tools will be able to quickly detect, judge and handle various abnormalities by themselves alone in the near future.

(2) The retrieving process for the machine tool interface

In the model, decisions (circle arrows) are made in the cyber space in connection with information on almost all of components in the cyber space. Meanwhile, *D-Operator* is not given a judgment function, and there is an information flow connecting *Operator* in the physical space with *D-Work* through *D-Operator*. This does not mean judgments by *Operator* are not necessary. It rather shows *Operator* in the physical space detects abnormalities of machine tools and conditions of work, makes local decisions about the production plan, quality control and other various topics, and gives specific directions through operations of machine tools and work. (Model components representing workers and work groups such as *Operator* and *Quality Control*, which are circled in the physical space are assumed to make judgments tacitly by themselves, and the corresponding arrows are omitted.) In the meantime, a next-generation machine tool that is essential for the cyber-physical manufacturing system enhanced with collective knowledge is required to be equipped with intelligence to complement the operator's judgments and knowledge from experience, so that more operator-friendly production will be realized. Such a machine tool is also expected to have the interface to retrieve information needed for that goal from the work environment.

Table 5.1 shows types of data on the interface of machine tools that can be collected through the analysis of use cases. Data categorized into the machine tool in the physical space is information that should be obtained from machine tools at factories (*Machine Tool*) to realize the use cases. Meanwhile, data categorized into the machine tool in the cyber world (*D-Machine Tool*) is information that should be owned by the internal model of the machine tool and referred to in order to build models for other components. For purposes of those types of data, see the table for each use case. As Table 5.1, of course, is not made based on the results of analysis of all possible use cases, it does not cover the interface of all general machine tools. The table should be modified when analyzing new use cases, and the data categorization method could be further improved. However, analysis of the use cases based on the modeling of the manufacturing system showed what type of information is provided to the interface and how such data is transmitted can be clarified.

Table 5.1 Data on the analyzed machine tool interface

Component name	Item	Remarks
Machine	Physical movement data	Information such as current position, speed, location, load, temperature and electricity for each axis
Machine	Machining records	Difference between planned and actual values measured in seconds
Machine	Operating status	Whether machines are working or suspended
Machine	Operating records	Basic information measured in seconds to check production line conditions (machining, being suspended, setting off alarms)
Machine	Unit information	How often relays, switches, magnets, condensers and other units are used
Machine	Alarm information	Detailed information on set off alarms. Information provided when alarms are set off.
Machine	Equipment information	Profile used to interpret alarm and machine conditions
Machine	Program number	0 number. Measured in seconds to check machining conditions.
Machine	Maintenance forecasts	Day maintenance becomes necessary is informed
Machine	Machining information	Such as NC program names and sequence numbers
Machine	Equipment degradation information	Servo axis information (electric current, deviation) [%, mm]; vibrations, sounds and temperatures of parts (motors and ball screws); tool abrasion levels
D-Machine	Diagnosis data	Users' provision of information to manufacturers, sharing of trends of multiple machines and tools
D-Machine	Judgments	Machinery information judged by workers based on threshold and other elements
D-Machine	Degradation forecasts	Performance degradation and when machinery will break down are forecast

D-Machine	Decision-making in emergency	Information on directions given to machine tools in emergency (such as steps to be continued or suspended, work processing, and whether to redo operations)
D-Machine	Degeneracy movement directions	Directions such as ones to reduce machining speed in order to continue production
D-Machine	Abnormality information	Information sent to conduct maintenance when performance degradation detected

(3) Toward controlling accessibility to information on the interface

The results of analysis of the use cases in the previous chapter made clear abstract information flows based on the purposes of each use case. When hoping to clarify the characteristics and problems for certain cases in the stages of putting smart manufacturing into practice (considering introducing a specific business model), which relevant parties in and outside the factory should refer to and update such information needs to be considered.

For example, a case where more than one worker is involved in a certain operation is examined as follows. To consider problems associated with personal information and trade secrets exchanged between the related parties in that instance, production facilities and information providers need to be specified as extra categorization criteria so that whether certain information is accessible (inaccessible) to appropriate (inappropriate) parties can be evaluated. Meanwhile, in order to consider issues related to the security (e.g., information leaks) and processing speed, both components in the cyber space (i.e., the internal model of components) and the mechanism to convert and process information between components need to be defined in connection with specific components in the physical space (such as machine tools and remote servers). The mechanism of encapsulation of information, which makes it possible to flexibly define accessibility to information depending on the types of information and who access the information, is an important factor to put smart manufacturing into practice. To design that mechanism for manufacturing systems of various sizes from small-scale networks at factories of small and midsize companies to large networks covering the whole value chain, the internal model of components and the mechanism to convert and process information need to be defined in connection with components in real space as described above. Preconditions (e.g., the scale of factories, configuration of equipment and characteristics of networks), use cases (e.g., services to be realized), risks (e.g., phenomena that could occur during provision of services and should be avoided), and other features are also necessary to individually design the mechanism of encapsulation of information.

6. Conclusions

A model of the cyber-physical manufacturing system enhanced with collective knowledge is a mechanism to realize future smart manufacturing, which will fully use not only all types of information collected through manufacturing systems but also workers' decision-making and other "kaizen" on-site improvement activities. The report has shown three important use cases based on the theme of productivity improvement, so that we can analyze the characteristics of the machine tool interface designed to retrieve the results of plant workers' decision-making associated with productivity improvement.

The analysis results showed information collected through machine tools includes a certain amount of information relating to on-site workers' advanced decision-making. Because of that, next generation machine tools will be required to be equipped with an interface to efficiently obtain such information. This is a common issue facing the machine tool industry and all relevant parties in the industry should work together to propose solutions to the issue. The consideration results in this report have won broad support from Japan's machine tool industry, and stakeholders involved in the lifecycle of manufacturing systems are currently working together to make preparations for building a cyber-physical manufacturing system enhanced with collective knowledge.

As a growing number of people in society come to see manufacturing systems as a kind of cyber-physical systems, various decision-making processes in manufacturing systems are expected to be automated, resulting in a drastic improvement in productivity. Despite those benefits, if information and models to be used in the cyber space are insufficiently prepared, results judged as "good" in the cyber space could not comply with the rules and common knowledge in reality (the physical space), causing serious damage to the real world. To prevent that from occurring, a cyber-physical system enhanced with collective knowledge should also flexibly refer to on-site workers' decisions.

As the birthrate continues to decline and the population ages in Japan, the production worker population in the nation is expected to decline drastically in the future. To realize a cyber-physical manufacturing system enhanced with collective knowledge, it will be necessary to optimize the balance between automated decision-making processes based on all kinds of information collected through manufacturing systems (with artificial intelligence and other technologies) and decisions by on-site workers who have knowledge on the facilities. Depending on the country and region, the working demographics, the work style, the proportion of lifetime of installed manufacturing systems, and other factors differ greatly. Nevertheless, the basic idea of cyber-physical manufacturing systems enhanced with collective knowledge will likely be able to be put into practice even for manufacturing systems outside Japan, while effectively using the characteristics of the country and region.

For realization of the vision of smart manufacturing as illustrated in Chapter 2, the next step of our work includes application of the proposed information modeling to visualization and evaluation of various important issues such as the integration of supply chains and engineering chains and cyber security such as information leakage with use cases.

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