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Smart Factory Information Service Bus (SIBUS) for manufacturing application: requirement, architecture and implementation

SooCheol Yoon[1] · **Jumyung Um**[2] · **Suk-Hwan Suh**[3] ·
Ian Stroud[4] · **Joo-Sung Yoon**[5]

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Abstract The Smart Factory is an important topic worldwide as a means for achieving Industry 4.0 in the manufacturing domain. Contemporary research on the Smart Factory has been concerned with application of the so-called Internet of Things (IoT) to the shop floor. However, IoT in this context is often restricted to solving local problems such as managing product information, collaborative information exchange, and increasing productivity. To take full advantage of the potential of the IoT in manufacturing systems, it is necessary that the information service perspective should receive keen attention. This paper proposes a reference architecture for the information service bus or middleware for the Smart Factory that can be used for information acquisition, analysis, and application for the various stakeholders at the levels of Machine, Factory, and Enterprise Resource Planning. To reflect the real voice of the industry, real industrial problems have been identified, transformed into requirements, and incorporated into the information architecture; i.e., Smart Factory Information Service Bus. The implementation process of the reference architecture is also presented and illustrated via case studies.

Keywords Smart Factory Service · Information Service Bus · Manufacturing Information Pipeline · Smart Factory Implementation

✉ Suk-Hwan Suh
shs@postech.ac.kr

SooCheol Yoon
darkhell@postech.ac.kr

Jumyung Um
jumyung.um@smartfactory.de

Ian Stroud
ian.stroud@epfl.ch

Joo-Sung Yoon
jsyoon@kitech.re.kr

1 Department of Industrial and Management Engineering, Pohang University of Science and Technology (POSTECH), 77, Cheongam-Ro, Nam-Gu, Pohang, Gyeongsangbuk-Do 790-784, South Korea

2 Technologie-Initiative SmartFactoryKL e.V., Trippstadter Strasse 122, 67663 Kaiserslautern, Germany

3 Center for Ubiquitous Manufacturing, Graduate School of Engineering Mastership, Pohang University of Science and Technology (POSTECH), 77, Cheongam-Ro, Nam-Gu, Pohang, Gyeongsangbuk-Do 790-784, South Korea

4 SGM - Enseignement SGM-ENS, Ecole polytechnique fédérale de Lausanne (EPFL), 1015 Lausanne, Switzerland

5 Smart Manufacturing Technology Group, Korea Institute of Industrial Technology, 89, Yangdaegiro-Gil, Ipjang-Myeon, Seobuk-Gu, Cheonan, Chungcheongnam-Do 31056, South Korea

Introduction

Manufacturing has been highlighted as one of the key aspects of modern global industry, and the concept of the smart factory is emerging as the next manufacturing paradigm. The smart factory refers to "Internet-of-Things"-based (IoT-based) manufacturing systems capable of improving total manufacturing performance reflecting the requirements of stakeholders as a means for achieving Industry 4.0. There are many definitions and descriptions of the smart factory, but most have the following aspects in common:

1. Components in smart factories are networked and it is possible to collect useful data from them.
2. The current status of manufacturing components can be determined and visualized in real time.
3. Autonomous and automatic processes can be executed based on optimized manufacturing plans.

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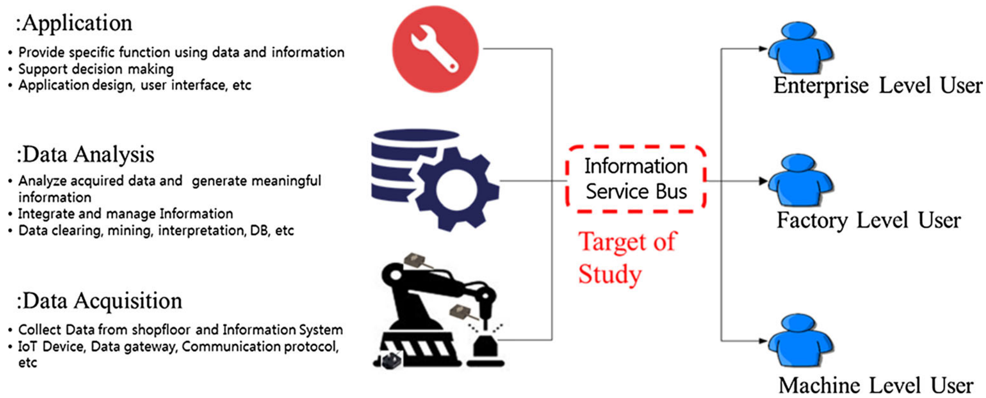

Fig. 1 Information perspective of Smart Factory

4. Advanced manufacturing services can be provided on shopfloor and to external systems.

Smart factories are currently being developed in advanced countries to solve problems resulting from short product lifecycles, lack of experienced workers, environmental regulations, separated manufacturing systems, and massive customer requirements. Previously, ubiquitous (Suh et al. 2008), lean (Bamber and Dale 2000), and holonic (Valckenaers et al. 1998) manufacturing systems solved some of these problems, but today's manufacturing systems require a wider solution covering whole manufacturing systems by active use of information. Much research is directed toward implementing the smart factory by utilizing information and communication technology (ICT) such as IoT, big data, and cloud computing.

In terms of information, the essence of a smart factory is how data are acquired, analyzed, and applied for the various internal and external stakeholders, as illustrated in Fig. 1. To access the full potential of the IoT for efficient data and information flow, a specialized information service bus is needed for manufacturing in a smart factory. This paper is concerned with such a bus, namely the "Smart Factory Information Service Bus" (SIBUS). The purpose of SIBUS is to transfer manufacturing information and services efficiently so that the total manufacturing performance can be improved (Fig. 1).

Previous research on data and information technology has been concerned with information content such as the design and exchange of product, process, resource (Lee et al. 2011; Wang and Xu 2012; Lee and Jeong 2006), manufacturing (Lee et al. 2012; Nassehi et al. 2006), monitoring (Bogdanski et al. 2012; Yang et al. 2015), maintenance (Espíndola et al. 2013), and refurbishment and recycling (Um et al. 2015). As far as information services are concerned, the ubiquitous product lifecycle support (UPLS) system has been proposed (Lee and Suh 2009). UPLS is an information middleware that supports product related activities in the design, manufacturing, usage, and disposal phases with product data models by utilizing real-time information occurring in each phase. However, since UPLS deals with product-oriented data, it is not suitable to be adapted as a smart factory information middleware. Smart factories aim to improve the overall manufacturing performance, so the data target should be the manufacturing system covering machine, factory and enterprise levels.

How to share and distribute information is also important in designing an information bus for a smart factory. Previous research adapted the manufacturing enterprise service bus (ESB) as an information middleware. This works mainly by integrating legacy applications in manufacturing systems such as manufacturing execution system (MES), supervisory control and data acquisition (SCADA), and enterprise resource planning (ERP) (Boyd et al. 2008). However, the traditional manufacturing ESB focuses on assisting business processes by linking information systems, and does not give much consideration to improving manufacturing performance or connecting with shopfloor elements.

Meanwhile, the concept of cloud based design and manufacturing has been suggested as a means of conveying manufacturing information and capability, and for achieving service-oriented manufacturing (Wu et al. 2013a, b, 2015). Based on the cloud manufacturing paradigm, several types of information middleware have been suggested to support various situations (Lu et al. 2014), cooperate with small and medium sized enterprises(SMEs) (Huang et al. 2013), and integrate product data through computer-aided design/manufacturing (CAx) process chains (Valilai and Houshmand 2013). However, the concept and its system are focused on product information and manufacturing capability, and do not support activities that occur on the shopfloor. Information middleware for smart factories should be able to support the information chain from data acquisition, to data analysis and application on the shopfloor for better performance.

As far as information content is concerned, previous research has mostly used productivity as the key performance indicator (KPI). However, the data and information content should be designed for wider purposes, considering other factors, such as environment and sustainability, which are increasingly emphasized in business. In other words, the information content and architecture should be designed to cover the various KPIs comprehensively. ISO 22400 (2014) defines KPIs for manufacturing operations management and representatively time, logistics, and quality related criteria are defined such as worker efficiency, throughput rate, and quality ratio. In this research, productivity, environment, and social impact are used as the components of the total performance index (TPI) of a generic smart factory, rather than focusing on specific KPIs.

Shin et al. (2015) proposed a TPI comprising productivity, environment, and society as a manufacturing performance indicator that combined effects related to products, resources, factory, and humans. KPIs and their weights are set according to the factory policy, as defined by the chief technical officer (CTO). Based on the TPI, all the manufacturing information should be optimized rather than focusing on one or a few economic criteria. In this paper, the TPI concept is kept in the design of SIBUS architecture.

Based on the state-of-the-art outlined above, this paper proposes a reference architecture for an information service bus or middleware for smart factories that can be used for information acquisition, analysis, and application by the various stakeholders at machine, factory, and ERP levels. In "Requirements of a smart factory", to reflect the real voice of the industry, real industrial problems are identified, transformed into requirements, and incorporated into the SIBUS architecture. In "Developing the architecture for SIBUS ", architecture is developed in detail based on the requirements. The actual implementation process of the reference architecture is presented in "Implementation procedure " and illustrated via case studies in "Case study ". The paper concludes with some remarks in "Remarks and conclusions ".

Requirements of a smart factory

In order to develop a realistic service information bus for a smart factory, it is necessary to analyze types of services have to be provided to the current manufacturing systems. Real manufacturing problems and TPI are developed for such a purpose. This paper presents problems that were identified during an international project carried out by the Republic of Korea and the European Union between 2010 and 2014, as well as interviews with people on the shop floor (Table 1). Since the aspect of information and TPI are concerned, problems related to insufficient information are highlighted. Hence, problems related to hardware are excluded, e.g., capabilities of machine tools and manufacturing processes. Note that the problems described below may not exist in the advanced manufacturing industry but in SMEs.

Table 1 Information related problems found in factories

Problem	Description
PR#1	Collecting shop-floor data in real time is difficult
PR#2	Machine level consumption analysis is not performed fully
PR#3	Performance evaluation is focused on only a few criteria
PR#4	Products and resources are manually identified by workers
PR#5	Information systems are not networked to each other
PR#6	Shopfloor environment conditions are not considered in production planning
PR#7	Predicting the result of a manufacturing operation is difficult
PR#8	Shopfloor information is not fully used for production purposes
PR#9	Manufacturing strategy does not account fully for exceptional cases
PR#10	Decision-making on the shop floor is dependent on levels of worker expertise

Information related problems found in factories

- [Problem (PR)#1] Collecting current-status data from the shop floor in real time is difficult. As a result, it takes time to identify problems.
- [PR#2] Analysis of material consumption is conducted at factory level rather than machine level. This makes it difficult to know which machines or strategies are more efficient, and machine efficiency cannot be reflected in process planning and scheduling.
- [PR#3] Performance evaluation is focused on only one or a few criteria (e.g., material removal rate and machining time). This can result in biased analysis from CTO defined policy.
- [PR#4] Products and resources are manually identified by workers. Manual identification can increase processing times with less reliability, and there remains the risk of errors due to human overload.
- [PR#5] Information systems work individually and are not networked to each other. There can be information gaps in processing operations with the potential for problems such as low quality, reworking, and overworking.
- [PR#6] The production plan is scheduled without considering the current shopfloor environmental conditions. Temperature, humidity, or other environmental conditions can affect product quality. Without such considerations, quality cannot be guaranteed.

- [PR#7]. It is difficult to predict the outcome of a manufacturing operation. There are gaps between the process plan and results in terms of product quality and production time, which eventually leads to lower manufacturing efficiency.
- [PR#8] Shopfloor Information is mainly used for enterprise purposes rather than production purposes. There is no feedback to production planning and scheduling from such information, so manufacturing operations do not improve.
- [PR#9] Manufacturing strategy is oriented more toward regular operations than exceptional cases. Machines or production lines cannot easily respond to varying conditions, delaying maintenance and operation times.
- [PR#10] Decision making in shopfloor is dependent on worker's knowledge. Knowledge differentials lead to unbalanced work assignment between workers, and novices have fewer opportunities to develop their skills.

Transforming into requirements for SIBUS

The problems identified in "Requirements of a smart factory " need to be transformed into requirements for the information architecture; i.e., SIBUS. Such requirements can be thought of as design considerations in developing the architecture for the information bus. The requirements are derived in terms of three categories to be reflected in SIBUS architecture development (see "Implementation procedure "): (i) data acquisition, (ii) data analysis, and (iii) application service (Table 2).

Requirements for data acquisition

- [RAq#1] Current factory status monitoring: it is necessary to monitor the current status of factories including man, machine, material and method which are known as the 4Ms of the factory. This consideration is essential for proactive and preventive activities in operations, as well as for process planning and scheduling. For this, it is necessary to have data acquisition and monitoring for workers, machines, products, and process data. (To Solve PR#1, #4, #6, #9, #10)
- [RAq#2] Machine level material management: it is necessary to manage the material consumption of each machine. This capability is critical in process planning for improving environmental KPIs. It is necessary to measure the consumption of each material (e.g., electrical energy and coolant), and it should be possible to distinguish between states of the machine (i.e., idle, turning-on, ready, processing, and turning-off). (To solve PR#2, #3)
- [RAq#3] Independent and identical elements: it is necessary to manage the 4Ms in a smart factory identically, and they should be independent from certain processes or systems. With this consideration, context based services can be provided. For this, 4M element identification in various shopfloor situations is required (To solve PR #1, #4, #10)
- [RAq#4] System interoperability: it is necessary to communicate with internal information systems including ERP, MES, CAD/CAM, product lifecycle management (PLM) and databases, as well as with external systems. Factory operations can be speeded up through interoperability. For this, it is necessary to have a unified 4M data model, database network, and common communication protocol. (To solve PR #3, #5, #8, #10)
- [RAq#5] IoT in factory: it is necessary to network all 4M elements in the factory. They should communicate with each other and with information systems so that the shopfloor and its information are synchronized in real time. For this, it is necessary to have agent and sensor technologies. (To solve PR #1, #5)

Table 2 Transformed requirements for SIBUS

Requirement	Description
RAq#1	Should monitor current factory status
RAq#2	Should manage material consumption at machine level
RAq#3	Should manage 4M in a smart factory identically
RAq#4	Should communicate with internal and external information system
RAq#5	Should network 4M elements in the factory
RAn#1	Should analyze material consumption according to context
RAn#2	Should verify availability of a process plan before execution
RAn#3	Should evaluate manufacturing performance in productivity, environment and social impact
RAn#4	Should trace factory 4M elements
RAp#1	Should control manufacturing operations autonomously
RAp#2	Should generate process plans and schedules considering actual shopfloor conditions
RAp#3	Should manage performance of manufacturing process from a holistic viewpoint
RAp#4	Should change information between various information systems
RAp#5	Should model and run simulations for process plans
RAp#6	Should treat generated information in real-time
RAp#7	Should support workers in various situations

Requirements on data analysis

- [RAn#1] Intelligent consumption analysis: it is necessary to analyze material consumption according to the information usage context. It should be analyzed under various conditions for evaluating and managing environmental performance, especially for energy consumption.

For example, it should be possible to analyze the energy consumption of a single work center in producing a product or to compare the consumption of different machines. (To solve PR #2, #3)

- [RAn#2] Verified process plan: it is necessary to verify the feasibility of a process plan at machine, factory, and enterprise levels. A verified process plan reduces the probability of operational risks such as failure, malfunction, or poor quality. For this, it is necessary to derive requirements and constraints of materials, machines, production line, workers, and existing plans and schedules from the process plan, as well as to check their availabilities. (To solve PR #6, #9)
- [RAn#3] Intelligent performance evaluation: it is necessary to evaluate manufacturing performance from the perspective of productivity, environment and social impact. It should also be possible to predict the performance from the process plan and schedule. The current factory level can be determined and further goals defined through this capability. (To solve PR #3, #6, #7, #10)
- [RAn#4] Traceable factory elements: it is necessary to trace the 4M factory elements. Here, traceability covers holistic characteristics of each element, not only physical location. With traceability, it is possible to make on-site decisions quickly. For this, it is necessary to ascertain the current status of each element (e.g., location, mode, failure, history, and further schedule). (To solve PR #1, #4, #6, #10)

Requirements on application provide

- [RAp#1] Autonomous control: it is necessary to control manufacturing operations autonomously by the system itself. Since the manufacturing plan does not usually describe how to react to events, it is necessary to determine this for each of the 4M elements for better efficiency. For this, it is necessary to have ontologies and context reasoning technologies. (To solve PR #6, #8, #9)
- [RAp#2] Field-based process plan: it is necessary to generate process plans and schedules considering actual shopfloor conditions. Process plans that assume ideal conditions can cause a series of operational problems. In order to avoid this, it is necessary for process planning to reflect realistic information such as availability, capacity, or constraints of manufacturing resources. (To solve PR #6)
- [RAp#3] Holistic performance management: It is necessary to build, evaluate, and manage performance of manufacturing processes from a holistic viewpoint. Holistic performance management clearly describes which points have to be improved, and it is possible to detect changes in performance quickly. For this, a performance model must be built and it should be possible to instance the model for evaluation and prediction. (To solve PR #6, #7, #8, #10)
- [RAq#4] Networked information system: it is necessary to exchange information between various information systems. Data and information generated on the shopfloor can be used beneficially in other systems in the company, and are also useful for external stakeholders. (To solve PR #5, #8)
- [RAp#5] Modeling and simulation: it is necessary to model and run simulations for process plans. Through simulation it is possible to discover process plan defects. The best alternatives for process parameters can then be chosen without compromising performance. (To solve PR #3, #6, #7, #10)
- [RAp#6] Real-time information treatment: it is necessary to treat the generated information in real-time. Manufacturing performance improves with faster response to events occurring during operation. This consideration is critical in rapid smart factory applications. (To solve PR #5, #8)
- [RAp#7] Manufacturing assistance: it is necessary to support workers in various situations. Expert knowledge is required in many manufacturing areas. However, not all workers are not equally skilled, so proper support is needed. Manufacturing assistance improves quality and reduces working time. For this, it is necessary to have knowledge libraries, cognitive, ontologies, and various support protocols. (To solve PR #8, #10)

A smart factory should aim to improve TPI, and the requirements reflect this. When reviewing the requirements according to the sequence of information flow, a smart factory should be able to:

1. Collect manufacturing data,
2. Analyze the data to derive useful information, and
3. Provide this information to the applications that use it.

That is, all requirements are ultimately related to applications, and requirements on applications (RAp#1–7) can be analyzed from the TPI perspective as follows. Most requirements related to productivity occur because of the natural characteristics of a manufacturing system. Rap#3, a requirement for holistic performance, covers environmental improvement. RAp#7, requirements for work assistance, is related to sociality. In the next section, the concept and architecture of SIBUS will be developed based on these requirements, leading to an improvement in TPI.

A final remark is that all problems identified in "Requirements of a smart factory " are reflected in requirements. Figure 2 shows a mapping between problems and requirements.

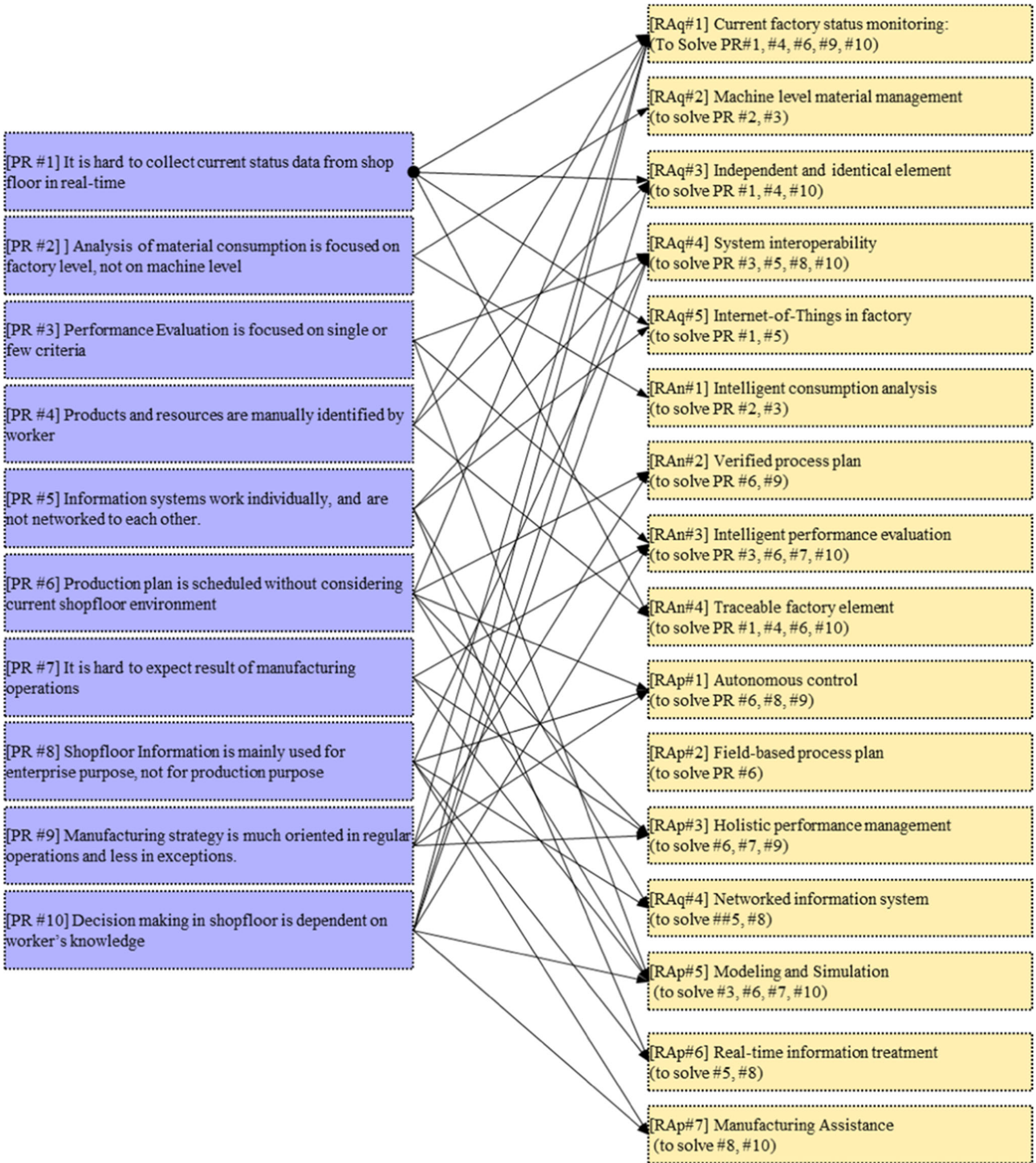

Fig. 2 Mapping between problems and requirements

Developing the architecture for SIBUS

The core of a smart factory is the delivery of manufacturing services to users. Service delivery is executed through manufacturing resources, service modules, information middleware and users, as shown in Fig. 3. It begins with a manufacturing resource that exists physically in the company for either operations or storing data and information. The service module attached to the manufacturing resource provides functions or information as a service. Information mid-

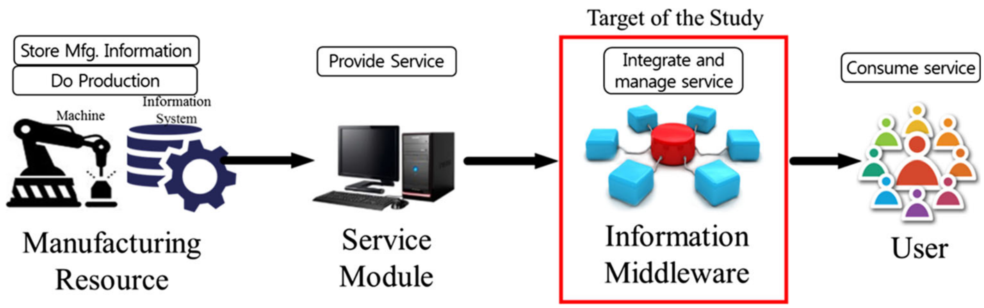

Fig. 3 Smart factory service delivery elements and target of the study

dleware integrates distributed manufacturing services and manages them for easier usage. Finally, users consume the services through the middleware. This paper sets the information middleware as the target system, namely SIBUS. In this section, a conceptual model of SIBUS will be developed that reflects its role and significance in delivering smart-factory services. The SIBUS functional reference architecture will be developed to express the services that need to be integrated, managed, and delivered to improve TPI.

Vision of SIBUS

In order to develop information middleware it is necessary to specify what types of roles the middleware is expected to play in a smart factory. The role of the system can be described by a vision with abstracting the input, output, function and surrounding systems. In this section a vision of SIBUS will be proposed as a smart factory information middleware.

A smart factory is expected to provide various services for improved manufacturing performance based on manufacturing information. A service can be used for a specific purpose, but is often used jointly by various users. However, it is not easy to find the desired service among numerous sources because the services are scattered all over the manufacturing system.

SIBUS acts as an intelligent information middleware that helps users to find the desired information and deliver the corresponding service by collecting, linking and summarizing distributed services as shown in Fig. 4. SIBUS provides services in a well-structured form with high speed and users can request services and get results easily and quickly. Here, SIBUS is defined as an information middleware for delivering the necessary services at machine, factory, and enterprise levels to improve TPI from the perspective of productivity, environment and social impact. In other words, SIBUS aims for the rapid delivery and management of information and services for improving TPI.

The SIBUS information service can be divided into four layers depending on the level and content of service. The first layer is the smart machine controller (SMC), which provides machine services such as machine data provision, control, and monitoring. The second layer is the smart manufacturing optimizer (SMO), which provides process preparation services such as process planning, scheduling, modeling, and simulation. The third layer is the smart manufacturing execution system (SMES), which provides process execution services such as operation control, performance evaluation, and maintenance support. The fourth layer is the smart enterprise content-management system (SECM), providing enterprise services such as history, knowledge, and performance management.

Characteristics of SIBUS

In order to realize the vision of SIBUS, four major functions are required:

1. Connect to the manufacturing services,
2. Itemize the services in a well-defined structure.
3. Describe the detail of each service, and
4. Manage service requests and their subsequent provision.

In this section, the characteristics of SIBUS for implementing each function will be introduced, followed by the development of the SIBUS functional architecture.

Conceptual aspects of SIBUS

If user-specific smart-factory services are provided by the middleware, rather than by separate and specific service providers, then the user feels as though the middleware is providing all the services. This is a simple description of the conceptual aspects of SIBUS and covers two functions required for it.

SIBUS is linked to each manufacturing system and delivers the results of services to users. SIBUS organizes all connections between users and service providers. When a user requests a certain service and receives the results, it feels as though they are using only SIBUS, even though they actually get the results from the service provider. SIBUS pro-

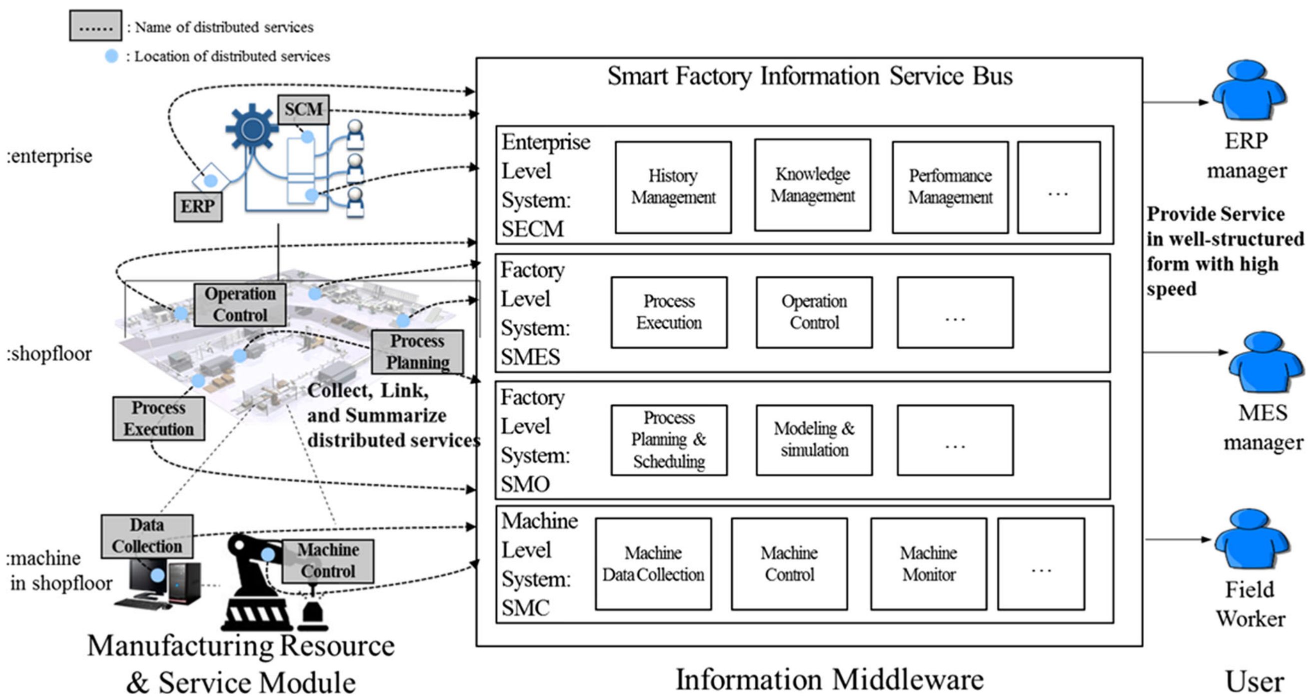

Fig. 4 Conceptual model of SIBUS

vides manufacturing system services in the form of a menu from which a user can choose the desired service and get the corresponding results. This can be described as the conceptual aspect of SIBUS, as shown in Fig. 5. In short, SIBUS plays the role of a trigger for performing actual smart factory services.

In addition, the conceptual aspect of SIBUS can allow services to be visualized with a well-defined structure. In principle, manufacturing services should be managed in a systemic structure, but this is difficult to achieve in real industries. Usually, many un-networked systems and services are distributed all over the factory. Now, SIBUS can describe these scattered services in a systemic structure as they are in a one-networked system owing to its conceptual aspects. In reality, the systems are at a distance but they are arranged and viewed in a systemic structure.

SIBUS service description language

Before requesting manufacturing services through the middleware, a user needs to know exactly which services can be provided. To deliver such details, the middleware should have a standard format for describing services. For this, a service description language should be defined for SIBUS.

Each service registered in SIBUS should give its name, description, specific function details, and required data. As shown in Fig. 6, the service should represent which functions will be executed, what information will be delivered, where the service provider is located, what type of input data is required, and what type of output will be generated. A SIBUS service description language has been developed for this purpose. The language is defined with XML and includes name, provider, description, location, input, and output of SIBUS services.

Service request process application

Various systems and users are connected through SIBUS. There are many issues in service provision, such as convenience, reusability, security, and different data models between systems. The middleware should support the interactions for efficient service request and process provision.

For this, the SIBUS process application modules for service requests are developed. There are six main modules of the unified product lifecycle data model: (i) process execution management, (ii) user authentication and data accessibility, (iii) user-defined process support, (iv) service search support, and (v) service history management. The general role of each module and the relationships between them, based on IDEF0 notions, are shown in Fig. 7.

- Unified product lifecycle data model defines the standard data model for the input and output of SIBUS services and manages the data format suitable for service usage (A1). This is necessary for supporting communication between service providing systems using different data models.
- Process execution management generates the logic for service provision and executes in a sequence (A2). It

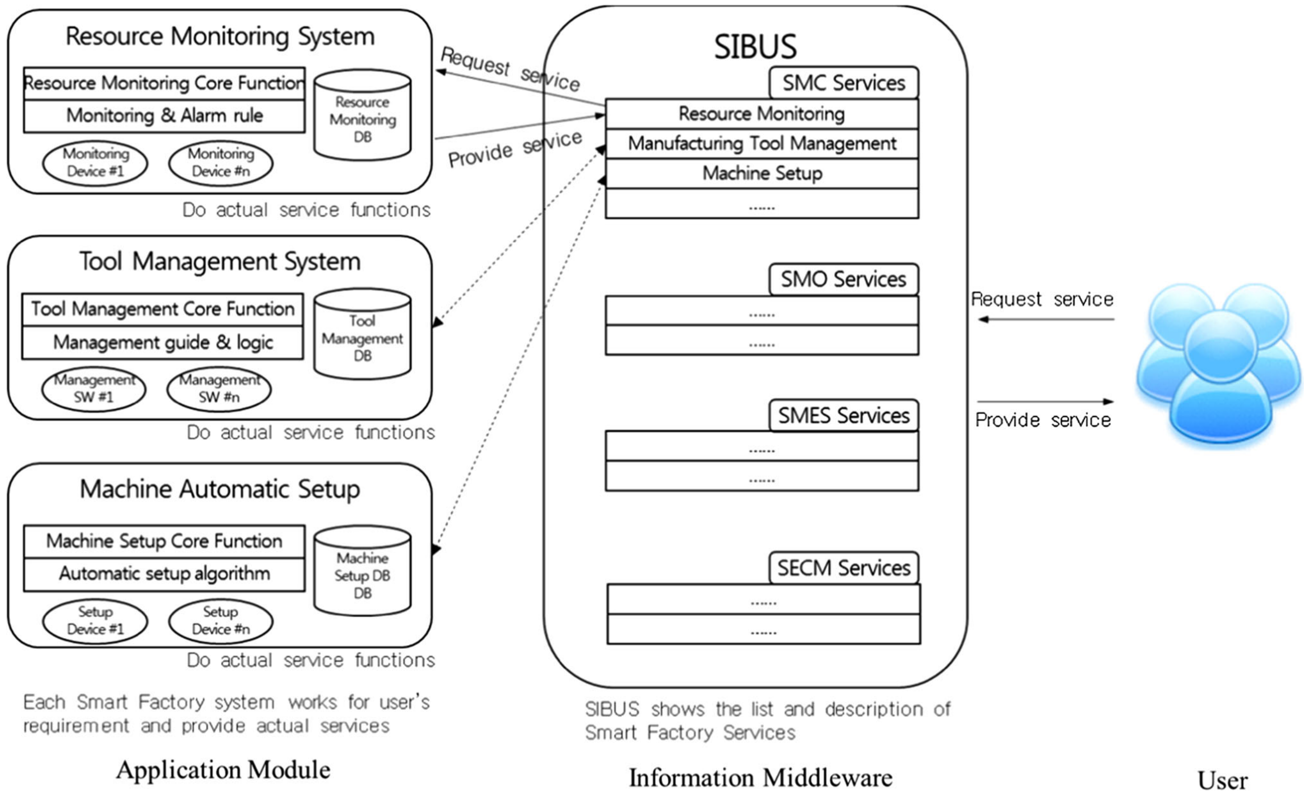

Fig. 5 Conceptual aspects of SIBUS

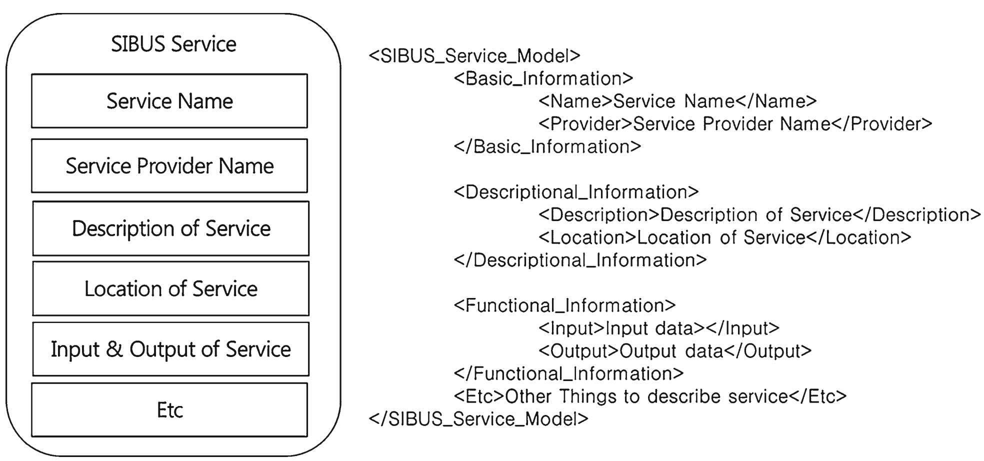

Fig. 6 SIBUS service description language

secures and maintains sufficient memory for the service from the time when a service request is received until the results of the service are provided to SIBUS, to ensure that the user receives the results of the service.

- User authentication and data accessibility execute a certification process for identifying a user who has authority for the service, and support quick service provision based on the service usage pattern of each user (A3).
- User defined process support provides a platform for defining and executing a series of services defined by the user when more than two services are to be used in a complex manner (A4). The process can be used repeatedly by being stored in the user's account and can also be shared with the user's group.
- Service search support provides a manufacturing service search engine so that users can find and choose a service based on SIBUS service details (A5).
- Service history management records service requests and provisions for each user and service, and supports the tracing process when unexpected events occur, such as a service error (A6).

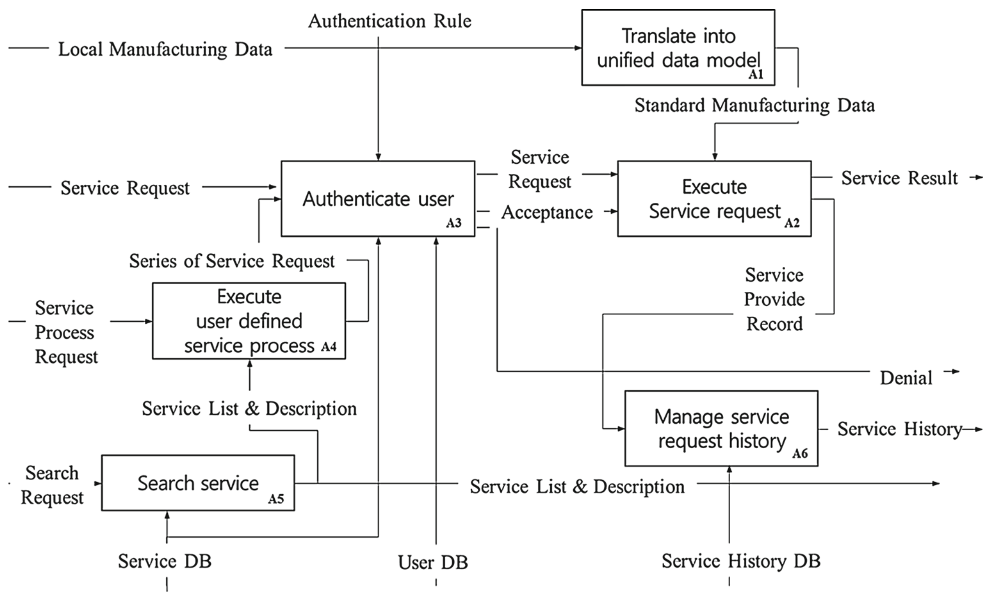

Fig. 7 IDEF0 diagram for process application modules

Reference architecture of SIBUS

The characteristics of SIBUS relate its functionalities as information middleware. However, the middleware aspect is not enough to satisfy the requirements of a smart factory. As stated earlier, a smart factory aims to enhance TPI through manufacturing services, so the middleware should reflect TPI perspectives. In other words, SIBUS should describe the types of services that should be delivered to enhance TPI. In this section, a reference architecture of SIBUS is proposed, with lists of services according to the service level. It is noted that the architecture focuses on the service that can be used in common by various users, following the requirements in "Requirements of a smart factory ".

By considering the smart-factory requirements, the manufacturing services and reference architecture for SIBUS are derived (Fig. 8). Each service is categorized as SMC, SMO, SMES, or SECM according to its characteristics, and each system can provide functions satisfying the smart-factory requirements. Each service is linked to an actual provider and describes the details according to the SIBUS service description language. Process application modules are applied for the sound use of each service.

The following are the details for each sub-system.

- *SMC* is composed of services for controlling and managing manufacturing machines. Intelligent resource control and monitoring services are defined, and it is possible to evaluate manufacturing processes at the machine level. Advanced services are possible including closed loop manufacturing, tool and resource management, and automatic setup for better production efficiency (Reflects RAqs#2, #3, #5; RAn#4; RAps#1, #8).
- *SMO* is composed of services for optimizing manufacturing processes. It provides machine-level process planning and services for sustainable TPI improvement. A performance model can be established and the expected performance can be achieved through manufacturing simulation. Manufacturing results can be adapted to existing models with corresponding updates. (RAns#2, #3; RAps#2, #3, #4, #6).
- *SMES* is composed of services for manufacturing execution. It provides services for manufacturing-process planning and execution. Factory elements can be monitored, performance can be measured at production-line and factory levels, failure can be detected and analyzed, and proactive maintenance can be achieved through SEMS services. In order to provide SMES services, much of the real-time information from the shop floor is needed and three smart agents (product, resource, and human) are designed as a sub-module of SMES supporting real-time service provision (RAqs #1–6; RAns #1, #3–6; RAps #1, #8, #9).
- *Product/Resource/Human agent*: Each agent is designed for managing individual factory elements. The product agent provides services for supporting the manufacturing progress of a product. Through the product agent, the location, product lifecycle information, processing information, and quality information are managed in real time. The resource agent provides services for monitoring the condition of a resource. Through the resource agent, it is possible to provide sensor data (e.g., temperature, vibration, and humidity), to identify the machine, to manage tool usage history, to conduct real-data-based maintenance, and to react quickly to unforeseen events.

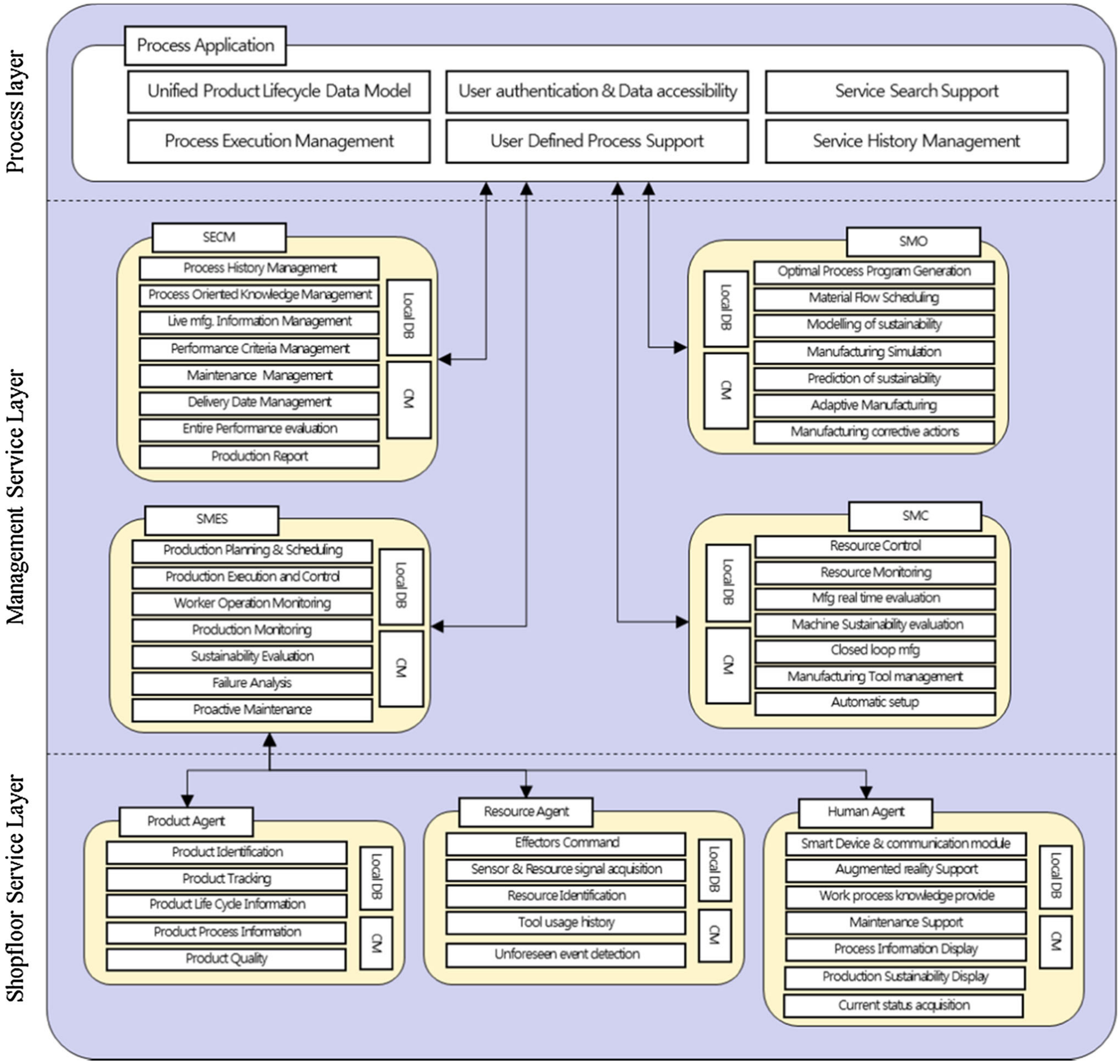

Fig. 8 SIBUS functional architecture

People are sources of data for some services and consumers of other services. Thus, the human agent contains two types of services: customer and provider. As a customer, the human agent provides support for smart-device usage (e.g., smart phone and tablet), augmented reality support, knowledge for manufacturing and maintenance operations, and other context-based information. As a data provider, it mainly reports the person's current state (RAqs #1–6, #8; RAps #1, #8, #9).

- *SECM* provides services for managing the information of a manufacturing system. Through SECM services, it is possible to manage manufacturing process history, knowledge for operation and control, real-time manufacturing information, criteria for process evaluation, and maintenance information and knowledge. The delivery date can be controlled in conjunction with a process plan and performance can be evaluated on the entire manufacturing-system level. SECM generates reports for the operational results. (RAqs #7, #8; RAps #5, #8–10).

Implementation procedure

The SIBUS reference architecture presents the smart-factory services needed to improve productivity, environment, and

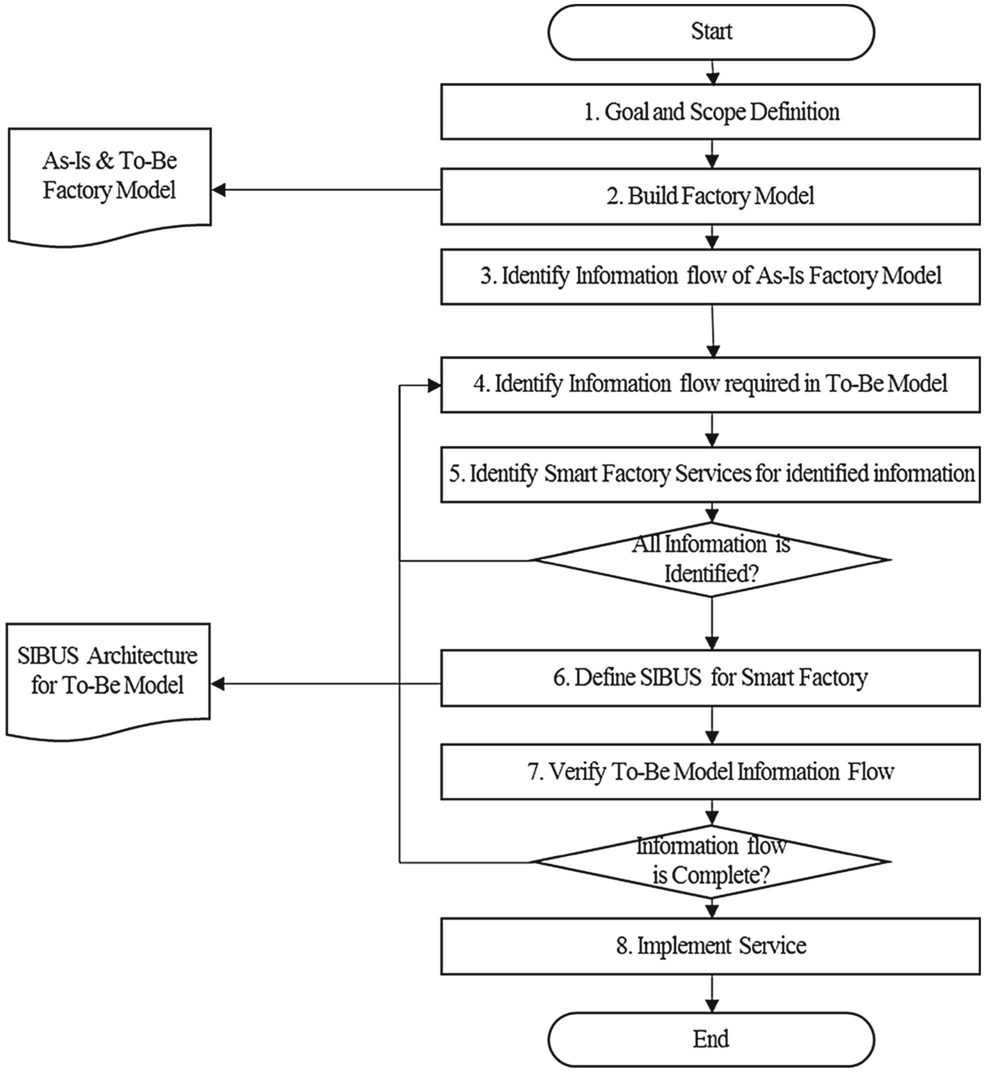

Fig. 9 Implementation procedure

social impact. However, not every manufacturing company needs to introduce all services at once when implementing a smart factory. Rather, they need services for each specific performance that requires improvement. For this, the company has to establish a set of essential services according to its goals. In this section, an implementation procedure for extracting such services is proposed based on the SIBUS reference architecture.

The methodology supports the identification of services to be implemented in the shopfloor and management service layers in the SIBUS architecture. The methodology also provides support in designing corresponding to smart-factory systems. The detailed design of an identified service is beyond the scope of this paper because each company has a unique environment so the service has to be detailed by the company. The process manager can be implemented directly without modification because it can be applied in common for the correct use of services.

SIBUS implementation consists of eight steps, as shown in Fig. 9, some of which can be operated repeatedly according to the implementing procedure. In particular, steps 4 and 5 are the core ones for determining smart-factory services and are carried out until all services and components are identified for the goal and scope of the system. The following are detailed descriptions of each step.

- *1. Goal and scope definition*: Define the goal of the smart factory to be implemented and the scope of the system. The goal represents performances to be improved in the manufacturing system, such as productivity, environmental friendliness, and sociality. The scope refers to the range of information the system has to include. For example, a scope may concern only one machine and one factory, or specific manufacturing cells.
- *2. Build factory model*: Build an AS-IS model representing current features of the manufacturing system and a

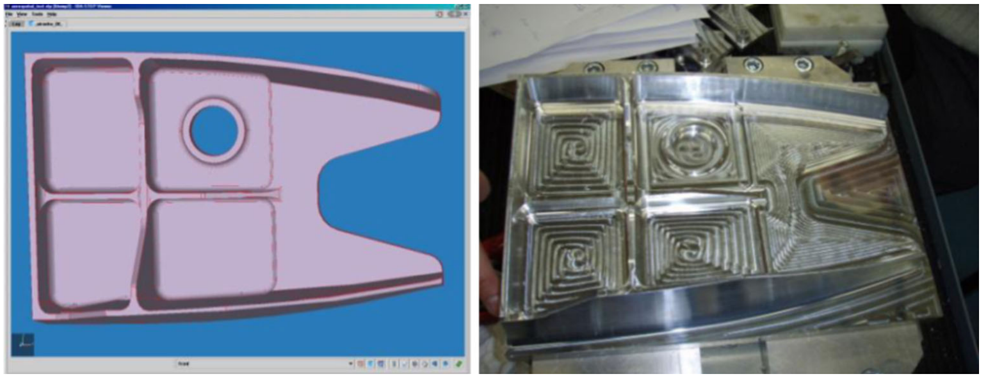

Fig. 10 Target product of case study: Fishhead

TO-BE one representing the manufacturing system after smart-factory implementation. In the latter model, the effect of the smart factory should be described. Each model has to show the factory elements, the level of each manufacturing process, and the manufacturing activity flow. The entire manufacturing system can be built in this step, but focusing on the part related to the goal and scope is sufficient.

- *3. Identify information flow of As-Is factory model*: Identify and describe the information flow of the current manufacturing system. The information flow shows the flows between elements and activities defined in step 2, as well as flows between external systems.
- *4. Identify information flow required for To-Be model*: Identify and describe the information flow to achieve a goal from the perspective of the data acquisition, data analysis and application provided. Information flow can be described as an effect or beneficiary of the service.
- *5. Identify smart factory services*: Define the services that provide the information identified in step 4. Generally, two types of services are defined: those that generate information and those that transport it. If all the information needed to achieve the goal is identified, go to step 6; otherwise, go back to step 4. Repeat until the source information service is defined.
- *6. Define SIBUS for smart factory*: Define SIBUS architecture by organizing the identified systems and services. Define detailed information of each service and assign a system that will actually work for the service. Define the data model for the identified information flow.
- *7. Verify To-Be model information flow*: Verify the information flow of the TO-BE model and whether all information and services have been defined sufficiently to achieve the goal. Specifically, check that information can flow continuously without interruption, that the goal and subject of each service are clear, and that the provider and customer of each service are clear. If any of these is not the case, go back to step 4.
- *8. Implement service*: Implement SIBUS and the service systems.

Case study

In order to show the validity of the SIBUS architecture and implementation procedure, it is necessary to apply them in an industrial context and show their effects. In this section a SIBUS case study aimed at the European aircraft industry will be developed. The target product is the “Fishhead”, shown in Fig. 10. In the case study, a smart factory system will be developed for better TPI using SIBUS architecture and its implementation methodology.

Case description

There are two actors in this case study: (1) the aircraft manufacturer, and (2) the fishhead supplier. The aircraft manufacturer chooses the supplier with the best performance among various candidates, orders the fish head, and takes delivery of the final product with its detailed performance, as shown in Fig. 11. There are two main operations: (1) best supplier selection, and (2) smart machining. The details of each operation are as follows.

Operation #1: best supplier selection

The objective of operation #1 is to choose a supplier who can guarantee the best manufacturing performance. To show how the manufacturing system will change, the current and target supplier selection operations will be described.

Currently, fishhead is supplied exclusively a specified supplier. Since there is only one supplier, the aircraft company cannot compare various alternatives for the product. It is difficult to achieve rapid supplement of parts in the case of unforeseen events such as poor quality.

The aircraft manufacturer is now trying to choose the best supplier from various feasible suppliers for rapid delivery and sustainable supply chain management. First, they issue a call for supply to feasible suppliers, containing production

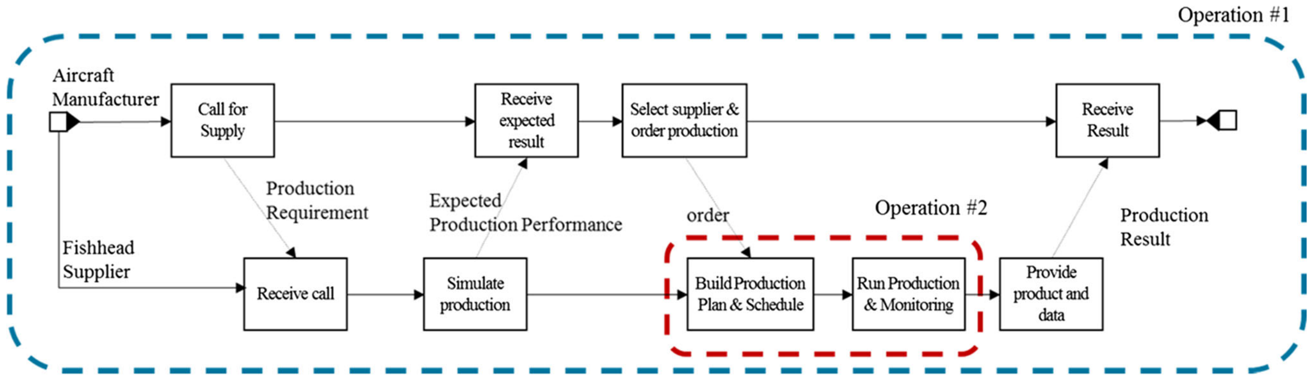

Fig. 11 Overall operations of fishhead manufacturing

requirements and CAD data. Each supplier runs a simulation of fishhead manufacturing based on their available resources, and reports the simulation results to the aircraft manufacturer. The aircraft manufacturer then selects the best supplier based on the expected performance and sends a production order. The selected supplier runs operations for fishhead manufacturing and monitors performance continuously during the operation. When the operation is finished, the final product and report are delivered to the aircraft manufacturer.

Operation #2: Smart machining

The objective of operation #2 is to build and run manufacturing operations for the fish head. Operation #2 specifies the building of a production schedule and the running of production and monitoring with detailed activities. As with operation #1, in this operation, the current and target operation will be described.

Currently, the supplier makes and provides the fish head on a sole-supplier basis. They provide the parts on time in the required quantity and have no specific manufacturing strategies. The status of operations and parts cannot be monitored.

According to a change in the customer's supplier-selection policy, the supplier needs to build a flexible manufacturing system. The supplier attempts to introduce advanced systems for simulation, production planning, and performance monitoring. First, they establish production scheduling to reflect CAD data and their requirements. Jobs are then assigned to machines considering the current plan, schedule, and machine capacity. For each machine, a STEP-NC part program is generated and run. During operation, performances in terms of product quality, energy consumption, and delivery time are monitored continuously.

Implementing SIBUS for the case study

To meet the requirements described in "Case description ", it is necessary to derive useful manufacturing services for the operations. In this section, the SIBUS architecture for the case study will be developed using the following implementation procedure. During the procedure, services needed for operations will be defined and the smart factory system, including information flow and factory elements, will be designed.

It is necessary to build the smart factory system and SIBUS in the supplier's manufacturing system since the actual manufacturing activities occur on the supplier side. The SIBUS architecture for the supplier is developed by following the implementation methodology described in "Implementation procedure " (Fig. 12). The implementation activities for each step are as follows:

- *1. Goal and scope definition*. The goal of the study is to improve general productivity, environmental friendliness, and social impact for the supplier at machine, factory, and enterprise levels. The study includes the elements described in "Case description " as the scope, specifically operator, machines for fishhead manufacturing, the produced fishhead, activities for simulation and process planning, and scheduling, production, and monitoring.
- *2. Build factory model*. AS-IS and TO-BE factory models for the supplier are designed as shown in Fig. 13. There are two levels in the model: (i) a conceptual figure describing the relationship between elements and (ii) an activity flow describing the manufacturing activities in a sequence. In the AS-IS model, operator and machine are the main elements. Activity flow is defined as consisting of received order, run production, and delivery product. In the TO-BE model, the manufacturing service system and product exist as elements in addition to operation and machine. It is possible to generate various alternatives, choose to achieve higher credibility of performance, and control and manage manufacturing activities. The activity flow is defined as consisting of receive call, simulate production, build production plan and schedule, run production and monitoring, and provide product and report. The activities can be divided into sub-activities, as shown in Fig. 13.

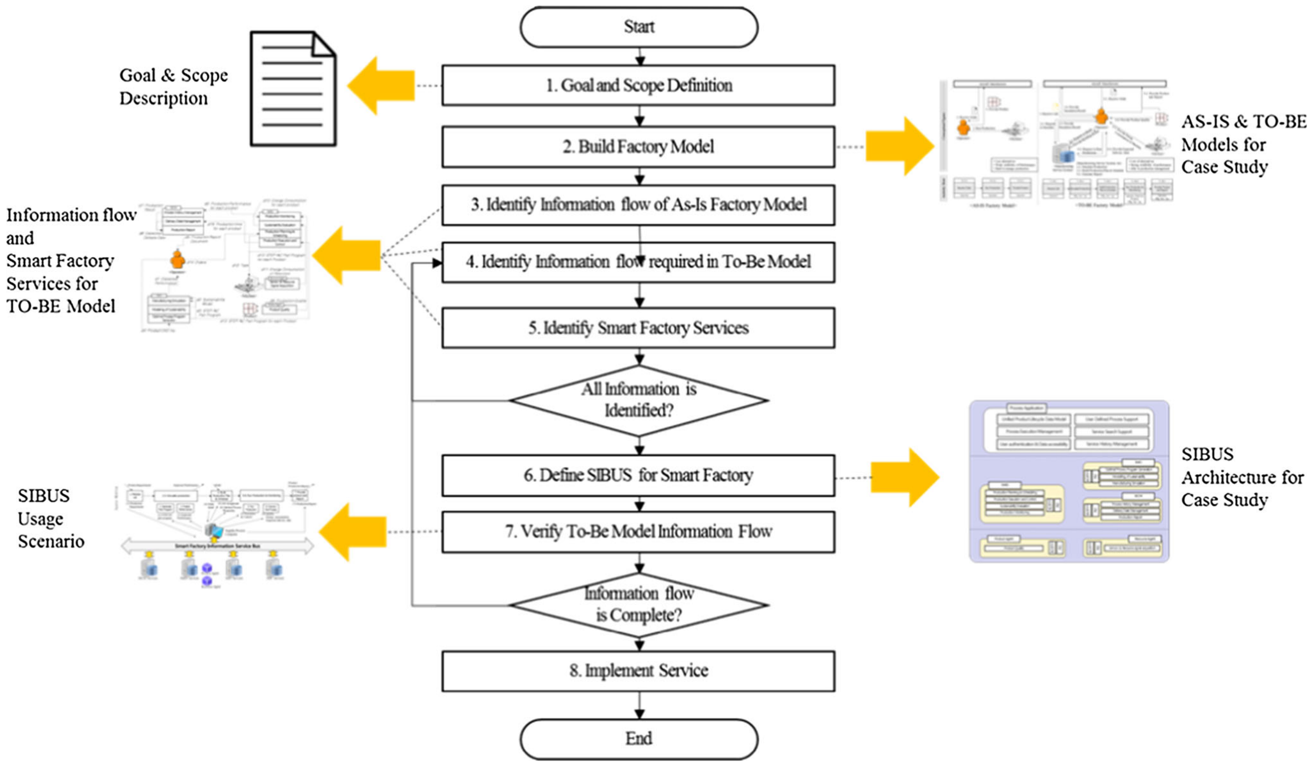

Fig. 12 SIBUS implementation procedure for case study with deliverables

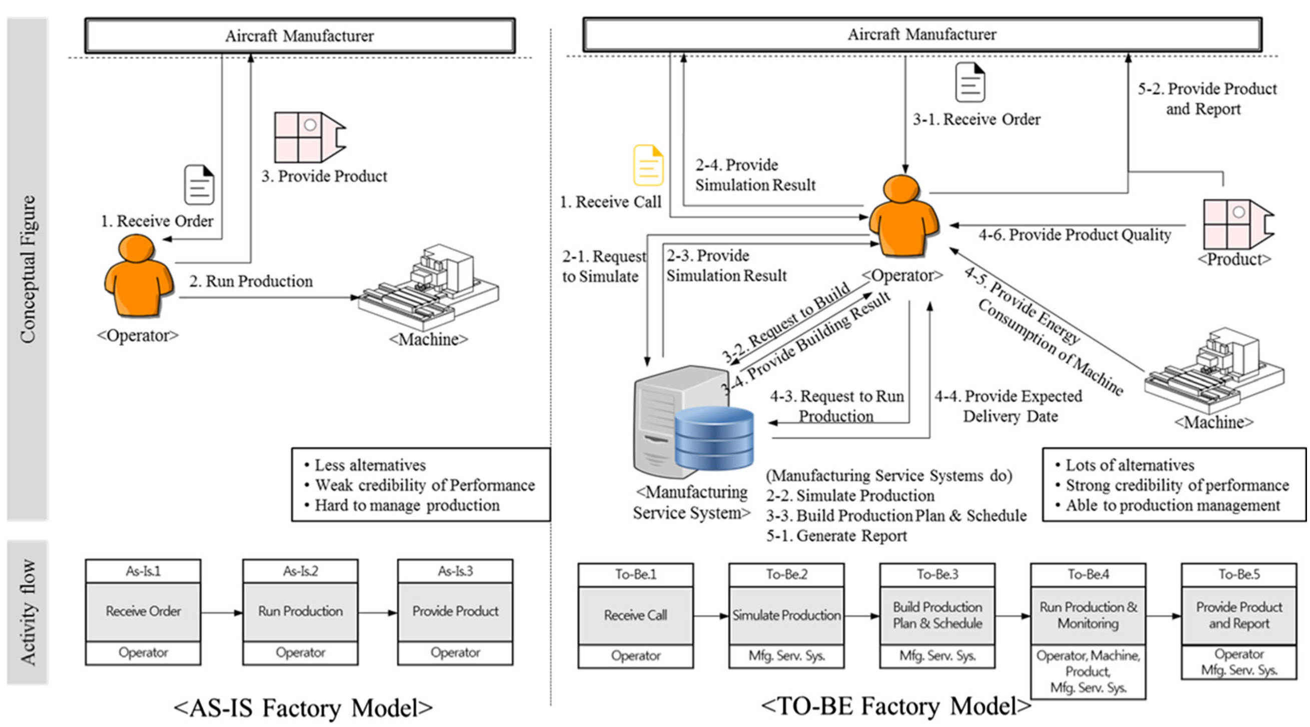

Fig. 13 AS-IS and TO-BE factory models

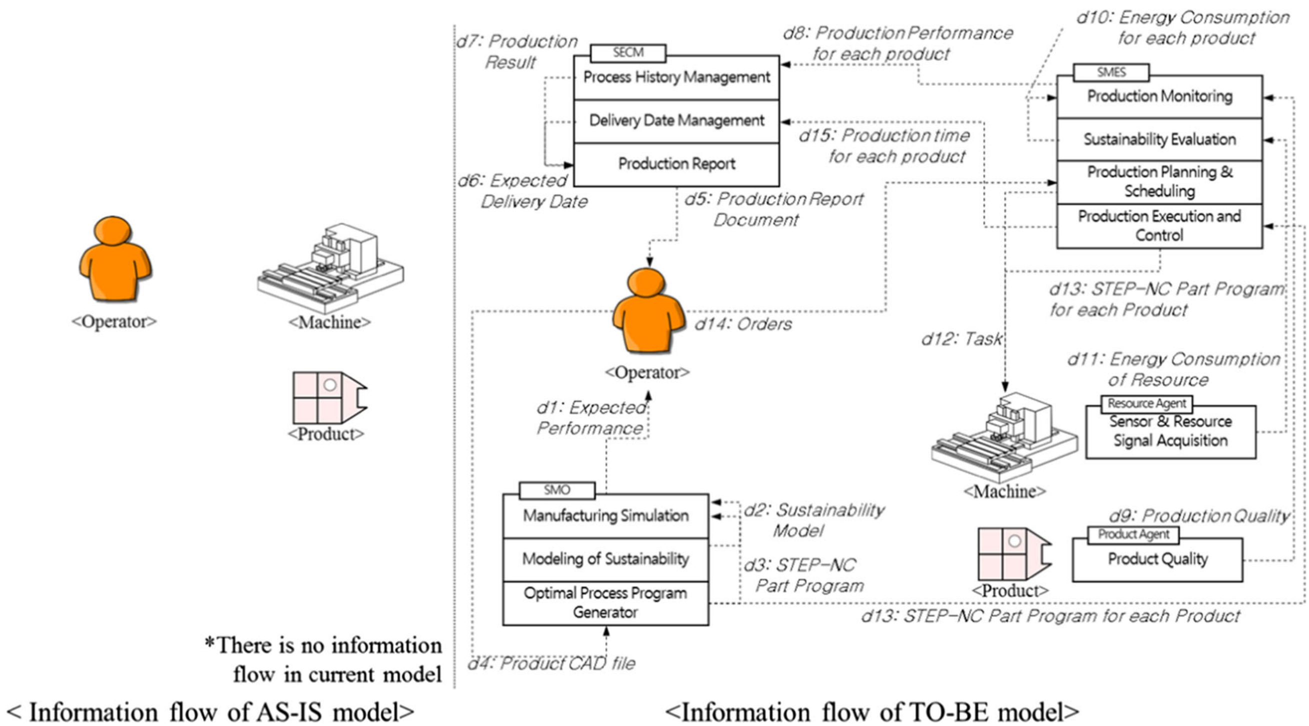

Fig. 14 Information flow of AS-IS and TO-BE model

- *3. Identify information flow of AS-IS factory model*. Since the production is conducted only with a physical object in the AS-IS factory model, no information flow is observed on the left of Fig. 14. The objects that exist are an operator, a machine, and the product.
- *4. Identify information flow required to To-Be Model and 5. Identify smart factory services*. Two steps are operated repeatedly, and 15 information flows and 12 smart factory services are identified. Since there would be too many descriptions for all activities in detail, identifying d1 through d4, and three SMO services will be introduced. First, the operator needs d1 (Expected Performance) to be communicated to the customer. d1 can be achieved with the Manufacturing simulation service, which in turn requires d2 (The sustainability model) as a performance evaluation reference and d3 (STEP-NC Part Program) as a target simulation process for service execution. d2 can be achieved with the Modeling of Sustainability service, which can be executed using internal database, and thus, the flow of identifying information for d2 stops here. d3 can be generated by the optimal process program generator service, which in turn required d4(Product CAD file) as a target of the process program. Because the operator already has d4 from the customer, the identification for d4 stops here. All services and data for d1are identified, and repetition for d1 ends here. Similar repetitive implementation of steps 4 and 5 for d5 (Production Report Document) is conducted as shown in Fig. 14.
- *6. Define SIBUS for smart factory*. SIBUS architecture for the supplier is developed by integrating the identified smart factory services as shown in Fig. 15. In addition to the 12 services, process application is included and local a DB and communication for modules are added to each sub-system. The Process application works to support the TO-BE Model activities described above.

The next step, 7 (Verify TO-BE Model information flow) will be operated in "SIBUS usage scenario ", and step 8 (Implement Service) is supposed to be operated in this study.

SIBUS usage scenario

Up to "Implementing SIBUS for the case study ", the smart factory system and the SIBUS case architecture have been developed. Using the developed system, it is possible to enable the target operation with an improved TPI. In this section, the SIBUS usage scenario will be introduced to show how SIBUS supports operations in a smart factory for the case study.

The scenario describes the supplier's manufacturing activities supported by SIBUS. Specifically, seven supplier activities will be described, as shown in Fig. 16. The first three activities describe the virtual manufacturing process of candidates and the rest describe the actual manufacturing process of the selected supplier.

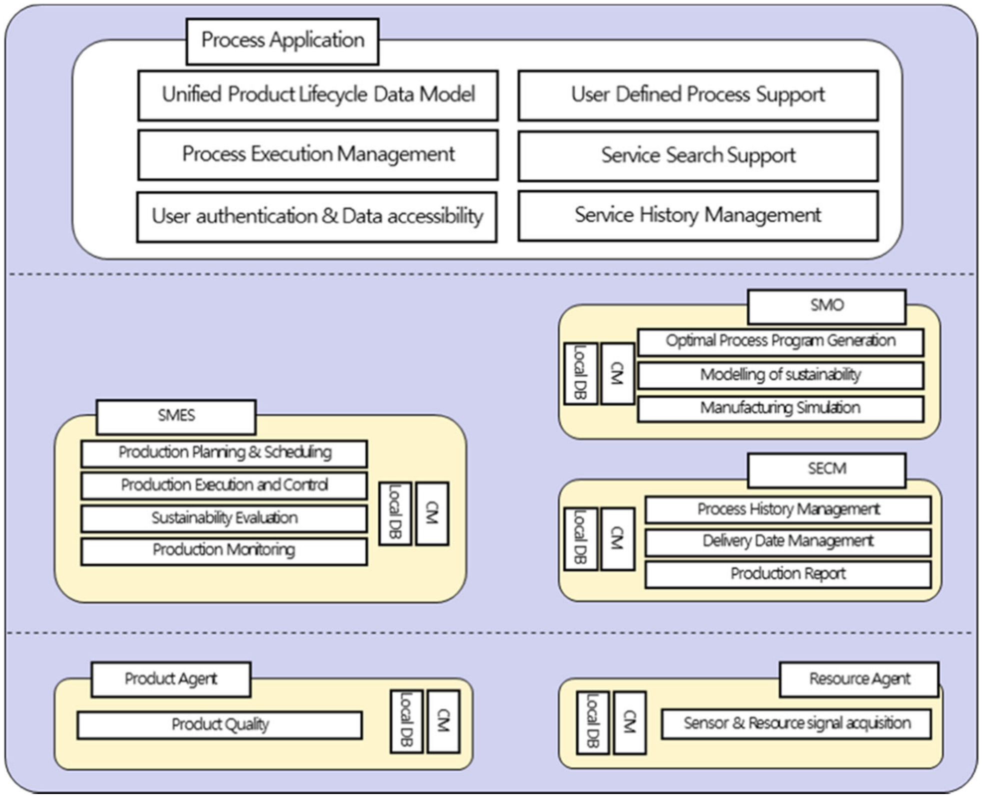

Fig. 15 SIBUS architecture for supplier in case study

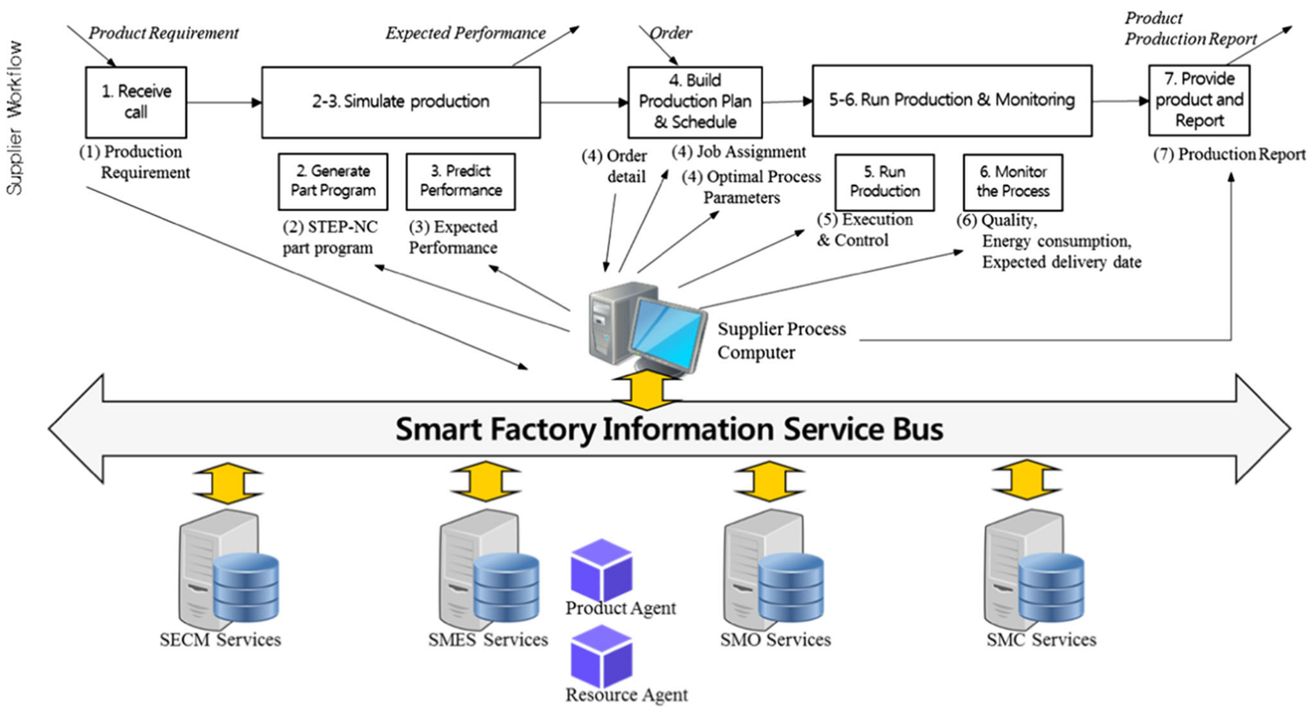

Fig. 16 SIBUS architecture operation scenario

- 1. In "Receive call", the requirements of the aircraft manufacturer are managed in a suitable way for the supplier's system. Production requirements are translated into standard data models by an interoperability ontology model. Quality specification, CAD data, and production due date are managed by the Unified Product Lifecycle Data Model. After translation and management, the data are converted into a standard format for the SIBUS platform.
- 2. In the "Generate part program," possible machines for fishhead production are identified and STEP-NC part programs are generated for each machine through SMO Optimal Process Program Generation.
- 3. In "Predict performance," virtual manufacturing is operated through SMO Manufacturing Simulation using the "Generate part program." The expected performances in terms of product quality, energy consumption, and delivery date under the defined condition are evaluated. SMO Modeling of Sustainability provides a relevant sustainable model for the expected performance evaluation. The supplier sends their machine availability and expected performance in terms of quality, delivery date, and energy consumption for the fish head to the customer.

After the first three activities, the aircraft manufacturing company chooses a supplier with the best expected performance and sends a production order that includes product quantity and quality, required delivery date, and energy consumption criteria. The chosen supplier builds a process plan according to the received production order and runs the associated operations.

- 4. In "Build production plan and schedule," an optimized process plan and schedule are built considering the current shop-floor status in terms of aspects such as machine schedules, expected operation time, and location of machines and logistics. SMES Production Planning and Scheduling determines the machines for operations and assigns new jobs for them. SMO Optimal Process Program generation sends a STEP-NC part program generated in the simulation step to the assigned machines.
- 5. In "Run production", manufacturing operations are executed according to the plan and schedule. The part program for each machine is executed by the SMES Production Execution and Control.
- 6. In "Monitor the process", SMES Production Monitoring monitors the manufacturing performance continuously during the operations. Production monitoring requests other services needed for monitoring various performances. Product quality information is gathered by product quality of the product agent. Energy consumption is achieved by a combination of SMES Sustainability Evaluation and Sensor and Resource Signal Acquisition of the resource agent. The latter measures the energy consumption of a machine continuously, whereas the former evaluates the amount of energy used in fish-head manufacturing. After all fish-head operations have been executed, SECM Process History Management stores the production-monitoring result and manages the quality and energy consumption information for each part. The expected delivery time is calculated by SMES Production Execution and Control according to the current status of manufacturing. SECM Delivery-Date Management manages the manufacturing progress, taking account of due dates.
- 7. When the fishhead manufacturing operation is finished, the SECM Production Report generates a report on the product and its associated operations, including performance information. The supplier sends this with the product to the customer.

Comparison with other middleware for case study

To show how SIBUS contributes to a manufacturing system, several existing middleware models are compared. For the case description in "Case description ", each middleware model including SIBUS can provide functions (Table 3).

SIBUS guides the construction of tailored manufacturing middleware, so the existing architectures or frameworks for developing middleware are compared. Numerous commercial products (e.g., SIMENS WinCC OA, iTAC MES Suite System, and Rockwell Automation FactoryTalk PharmaSuite) can collect manufacturing data and provide MES functions. These products can support in process monitoring, evaluation, and business contracts, but they are excluded from this comparison because they are a complete middleware package themselves and do not guide users to build their own middleware.

Many information-middleware models focus on low-level activities such as data collection and transport, or high-level activities such as business contract support. Gateway Operation System (Fang et al. 2013) and ebbits (Khaleel et al. 2015) suggest information middleware for rapid and flexible data collection from a heterogeneous machine and device. In the case study, these middleware systems can increase production efficiency by resource management and reconfiguration, and environmental friendliness by collecting and managing energy-consumption data. Hybrid Manufacturing Cloud, SME-CMfgSP, and XMLAYMOD aim to realize the cloud-manufacturing paradigm; these middleware systems use IoT and cloud computing technology mainly to help various business transactions. In the case study, they can support enterprise-level activities such as supplier selection, delivery management, and a CAx process chain.

The functions of these five middleware systems appear to be inadequate for the present case study. They seem to be

Table 3 Comparison of SIBUS and existing middleware

		SIBUS	Hybrid Manufacturing Cloud (Lu et al. 2014)	SME-CMfgSP (Huang et al. 2013)	XMLAYMOD (Valilai and Houshmand 2013)	Gateway Operating System (Fang et al. 2013)	Ebbits (Khaleel et al. 2015)
Main objective of middleware		Define services and data for improving KPI	Support various cloud modes for mfg. resource provide and use	Provide logic and structure for mfg. cooperation with SME	Integrate product data through CAx chain	Unify various identification device for flexible applications usage	Generate meaningful data from physical device
Supporting manufacturing activities							
Productivity	Enterprise	Factory Cooperation	Supplier selection & Delivery Management	Resource Sharing & Enterprise collaboration	CAD-CAM Chain	ERP/EIS	
	Factory	Factory Utilization & Work balance		Report manufacturing progress		Dynamic Resource Reconfiguration	Indoor Locating
	Machine	Process Optimization & Smart Machine Control	Product Design as a Service		STEP-based design & manufacturing	Device plug & play	OEE & Vibration Detection
Environment	Enterprise	Manufacturing Plan	Supplier Selection				
	Factory	Machine Selection					Overall Energy Management
	Machine	Resource Monitoring					Machine Energy Management
Sociality	Enterprise	Fair Trade	Fair Trade	Fair Trade			
	Factory	Machine Selection Assistance					Work Force Management
	Machine	Operation Parameter Selection Assistance					

technology-oriented systems, such as RFID, IoT, and cloud computing, with specific purposes. This characteristic also limits their application domain to either within or outside the shop floor. The most novel aspect of SIBUS compared to other middleware is that SIBUS aims to improve TPI according to the purpose of the stakeholder. Based on this property, it can support activities that improve productivity, environment, and sociality at the machine, factory, and enterprise levels, respectively. These activities can be factory cooperation, factory utilization, work balance, and smart machine control, which are all adequate for the case study.

In short, SIBUS contributes in two ways. First, it contains services from machine- to enterprise-level manufacturing activities, which is a wider coverage than that of existing middleware. Second, it helps to identify services and data that can be used to improve TPI according to the stakeholders' requirements.

Remarks and conclusions

This paper derived the SIBUS architecture as an information middleware based on current problems in Korean and European industries, especially for SMEs. This was followed by requirements on data acquisition, data analysis, and applications provided in a smart factory, as well as an exploration of the vision and characteristics of SIBUS. General services for improving TPI were defined at the four levels of machine control, process optimization, manufacturing execution, and content management. To apply SIBUS in a real industry, an implementation procedure was derived and applied to the aircraft manufacturing industry. This procedure was useful in designing smart-factory systems and identifying required services according to the purposes of stakeholders. SIBUS supports service exchanges at machine, factory, and enterprise levels as a middleware and provides lists of services for each level, reflecting general requirements to improve the TPI in terms of productivity, environment, and social impact.

To realize SIBUS and smart factories it is necessary to develop technologies for factory elements such as man, machine, material, method and environment. In particular, smart agent technology is needed to enable each element to provide a service. In addition, many platform technologies are needed to handle massive calls for services; basically platforms for machine learning, factory simulation, complex event processing, and distributed databases are needed, all of which are commonly required by current factories.

Based on the framework proposed in this paper, smart-factory platforms for cloud-based services based on manufacturing big data are being developed as an industrial project. Three types of platforms will be developed for seamless manufacturing information exchange, a real-time manufacturing big data platform, and a cloud-based service provision. Also, a holistic view of a smart factory adapting the cyber manufacturing system is under development. The system supports intra-factory application for better manufacturing efficiency and inter-factory application for enterprise cooperation with domain-specific implementation technology based on a system-engineering approach.

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