Research and Development of a Service-oriented Architecture for a Smart Factory Production System

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Abstract— **In this paper the possibilities of using a service-oriented approach for production systems architecture design are considered. The issues of a system architecture design process are studied on the example of the experimental Smart Factory for the manufacture of magnetic materials and products. The application of the V-model as a system engineering tool for Smart Factory design is presented and described. The use of simulation and simulation technologies for the implementation of the Smart Factory concept is shown.**

I. Introduction

The Smart Factory represents a key aspect of implementing, distributing, and scaling the technologies of the fourth industrial revolution. Factories are becoming smarter and more efficient thanks to the combination and integration of production and information and communication technologies, the development of an analytical culture and network infrastructure. At the same time, the concept of a Smart factory itself can be considered as a well-known model for organizing production systems. [1, 2]

The relevance of the work is to study the problem of creating efficient and optimal architectures of new production systems. Effective use and management of information, as well as system integration, can be achieved only if these processes ensure the management and exchange of data throughout the supply chain and product lifecycle.

The purpose of the work is to consider the possibilities of using a service-oriented approach for designing the architecture of production systems. At the same time, the application of simulation and simulation technologies for the implementation of the Smart Factory concept is of particular interest.

The described Smart Factory is an experimental Learning Factory for modeling, simulating and prototyping objects and technologies of real production systems. This factory is formed on the basis of educational laboratories of KSTU named after I. Razzakov (Bishkek, The Kyrgyz Republic) and ITMO University (St. Petersburg, The Russian Federation).

II. Background

A. Smart Factory, ICPS, ICP-Platform

In the context of the fourth Industrial Revolution, the term "Smart Factory" is widely used by both industrial practitioners and scientists, but today there is no generally accepted definition of it [3]. At the same time, the current volume of knowledge and publications on the subject under study confirms its high attractiveness and its special position in the academic and applied engineering communities.

Within the framework of this work, the authors have adopted and considered the following concepts:

Smart, intelligent production, Smart Factory – is a model of production organization based on the use of a flexible, adaptive architecture for building production based on the technologies of industrial cyber-physical systems. [4]

Industrial (Production) Cyber-Physical system – ICPS. In general, cyber-physical systems are understood as a network technical system consisting of digital (virtual) and physical systems (components) interacting with each other. [5, 6]

The Industrial Cyber-Physical Platform (ICP-Platform) is a design and development environment for industrial cyber-physical systems of the Smart Factory class.

B. Service-Oriented Architecture and Design Approach

Service-Oriented Approach is a design methodology based on the representation of a project as a set of services, each of which is a separate component with fixed interfaces that perform certain functions. [7, 8]

This design approach is based on the well-known *Service-Oriented Architecture (SOA)* [9, 10, 11]. The SOA as a model has many areas of application and it has been well standardized [12, 13, 14].

Due to the fact that SOA can be applied to a wide variety of tasks - depending on the direction of activity of specialists working with this architecture, there are three descriptions of SOA (viewpoints) – in terms of business direction, architecture, and implementation:

1) *SOA description from the business viewpoint* is a set of services that the business offers to its customers and partners or other divisions of the organization.

2) *SOA description from the IT architecture viewpoint* is an architectural style that requires the presence of the provider and user of IT services, as well as their descriptions. A set of architectural principles, patterns, and criteria that take into account characteristics such as modularity, encapsulation, weak connectivity, separation of interests, reusability, composability, and unity of implementation.

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3) *SOA description from the implementation viewpoint*. It is a programming model that is compatible with Web service standards, tools, and technologies.

The key concept of the SOA is interfaces. They are the means for presenting the capabilities of a particular service to users and organizing interaction between different types of services. The service interface defines the parameters for accessing it and describes the result, that is, the interface should define the essence of the service, and not the technology of its implementation.

SOA offers a single service interaction scheme, regardless of whether the service is located in the same application, in a different address space of a multiprocessor system, on a different hardware platform in a corporate intranet network, or in an application deployed on a partner's IT site. All this ensures the flexibility of SOA, the ability of the system implemented in such an architecture to respond to changes.

III. Development of the Service-oriented Architecture for a Smart Factory Production System

A. System Architecture for a Smart Factory Production System

Architecture is an abstract description of the behavior, state and properties of a system at the level of conceptual design, defining the key elements, the relationships between the elements and the basic principles of the design and development of the described systems. [4]

This Smart Factory architecture is designed to describe the different layers of the automation pyramid (in particular, the second and third), by providing a decentralized cloud infrastructure and methodology for connecting new and existing automation systems in accordance with the concept of network-based flexible production systems.

In this work the *Service-Oriented Architecture* has been used as a core model for an experimental Smart Factory production system architecture design and development. *The Service-Oriented Approach* has been used as a design methodology.

The specifics of SOA for Smart Factory application lie in the industrial domain. The industrial domain forms specific constraints and requirements to SOA and design approach, which should be considered during the Smart Factory life-cycle stages. [11], [15], [16]

On the one hand, the design and development of a system architecture for innovative production systems should take into account the functional requirements for ICPS, using existing advances in the field of design process automation (computer-aided systems, CAx) and manufacturing operations management (MOM). Meeting this condition should support backward compatibility of existing engineering solutions and research prototypes within the proposed system architecture.

On the other hand, the architecture should take into account current trends and prospects for the development of the design and organization of production systems, and comply with the currently developed standards and models of Smart Factory.

The analysis of the above requirements shows that the system architecture should:

1) be based on intelligent and heterogeneous components of the production system (industrial agents);

2) provide seamless reconfiguration and reconfiguration of the production system;

3) optimize planning, modeling, and simulation procedures;

4) provide administrative and informational support to the system operators.

The Smart Factory system architecture for seamless reconfiguration and reconfiguration of production systems involves the use of a decentralized management paradigm, as opposed to rigid and monolithic structures (ISA-95), which are not able to meet modern requirements for production systems.

Fig. 1 shows a system architecture consisting of a number of heterogeneous intelligent hardware and software components.

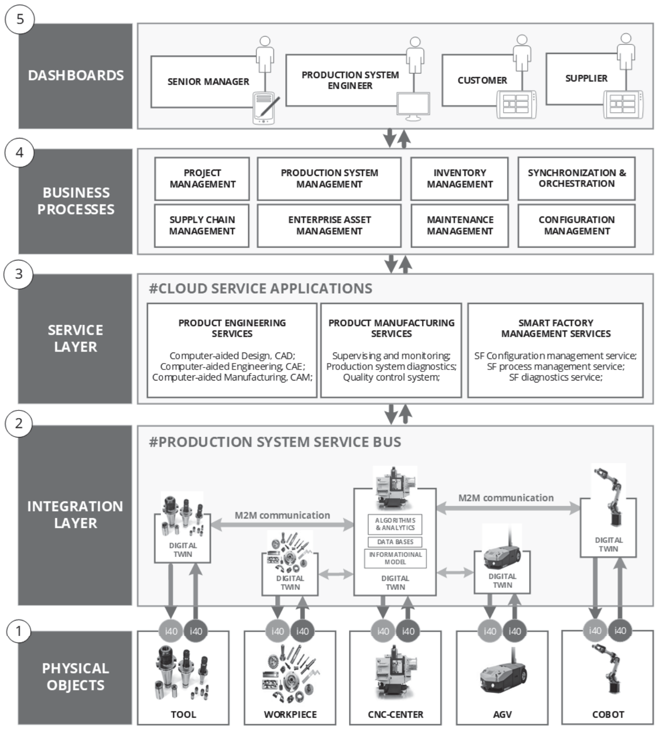

Fig. 1. System architecture of the experimental Smart Factory

The system architecture contains five layers. The first layer includes physical representations of production system objects, their hardware parts, and physical interfaces. An example of such objects can be a CNC machine for machining, an AGV robot, a billet of the future product.

The second layer contains digital representations of physical objects. At this level, the software part of the objects is implemented using digital twin technologies. These digital doubles contain all the necessary information about the object throughout its life cycle, and also have the necessary functionality for inter-machine and human-machine interaction in a heterogeneous production environment. In this case, each object is an industrial agent. A production system object provides its functionality as a service application at the next level of the system architecture. At the same time, the industrial agent encapsulates the hardware and software components of the object. This layer also implements the interaction of industrial agents with the service bus of the production system.

An Industrial Agent or I4.0 Agent is a component that represents a physical or logical object of the system that can interact to achieve its goal, and has the ability to interact with other agents if it is not able to achieve the goal on its own. It can act as equipment, robot, product, cell, tool, or human. [4]

The services layer provides the ability for various service applications to interact with industrial agents or other service applications. The number and composition of service applications is configured based on the tasks and purpose of each individual Smart Factory. At the same time, there are three basic groups: engineering services, manufacturing services, and production system management services.

The business process layer enables the integration of separate unrelated service applications and industrial agents into composite business process structures. These processes provide one of the three functions of the enterprise: management, execution, and support.

The data representation layer provides the ability to interact with the production system for individual users. These users have the ability to read and analyze the data provided by the production system in real time. At the same time, the information is provided in a convenient format of dashboards or web portals.

An important place in this system architecture is occupied by a single information space, within which information support for processes at each of the layers is provided.

As it has been mentioned before, the interfaces are the key concept of the SOA. It's quite important especially for Smart Factory application. Interfaces allow *an industrial agent* a capability to communicate with other production system layers by defined and standardized protocols (see OSI model, etc.). On physical level any of industrial asset (technological equipment, workpiece, etc.) has its own physical or logical interface to the its digital representation. This interface could be a PLC, or a special adaptor or a device, which allows the industrial asset to integrate itself to Production System Service Bus as *an Industrial Agent.*

Application Programming Interfaces (API) are commonly used on upper layers of presented *System Architecture*. There are well-known problems with software services integration, which are discussed in [17], [18], [19]. These researches discuss integration problems on different cross-layer applications for industrial domain (service-to-service, service-to-user, IoT device-to-service, etc.).

B. V-diagram methodology for design and development of Smart Factory SOA

The V-model serves as a methodological basis for designing a prototype of an experimental Smart factory (Fig.2). This model is widely used in systems engineering as a framework for the development of complex technical systems.

Consider the model from the point of view of creating a production system. The starting point of the design is the conscious need of the project customer. In this case, the need comes from the objectives of this study. Next, the initial custom specification is formed – the technical task for the design of the production system. This document contains a description of the purpose, as well as general functional and non-functional requirements for the designed system.

The next step is to analyze the requirements. This stage involves a detailed analysis of the requirements, their functional decomposition, as well as further elaboration and detailing of functional and non-functional requirements. Diagrams of usage, classes, and target states in visual modeling notations are described. The stage also includes an analysis of the state of the source system (if any), its maturity and readiness for changes. [20], [21], [22]

The development of the design solution involves the process of multi-level design of the production system. It describes its architecture – the composition and structure of the components. The choice of technologies, practices and methods is made. Models of production, technological and business processes are formed, describing the logic of the functioning of the design object.

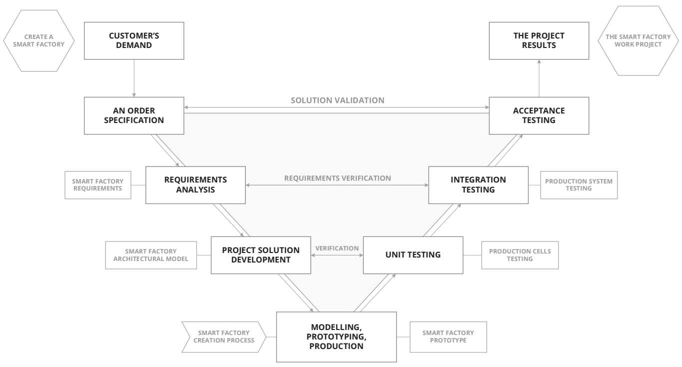

Fig. 2. V-design model of the experimental Smart Factory

The next stage includes the processes of complex object modeling and simulation, building functional prototypes, and manufacturing and integrating individual components into a single production system.

In the following sections of this study, some steps in the process of creating a Smart Factory prototype will be considered, for example, the methodology for developing individual service applications, the methodology for creating technical devices, the methodology for integrating modern and outdated technological equipment, as well as the methodology for setting up a digital cloud infrastructure.

The subsequent stages are associated with the evaluation, verification and validation of developed and implemented design solutions for compliance with functional and non-functional requirements at the levels of unit testing of individual components, integration testing of interfaces and module interaction, as well as acceptance testing for evaluating and validating a complete design solution. Positive completion of the testing stages ensures that the project results meet the expectations and needs of the customer.

C. Industrial Cyber-Physical Platform for Smart Factory design, modelling, and simulation

The idea to create a platform solution for production system is well-known. There are researches [23], [24] that discuss the idea to create and implement an industrial platform solution in specific domains. The paper [23] discusses the application of a service-oriented platform for dyeing and finishing industry. The paper [24] discusses the application of SOA, cyber-physical, and digital twin technologies for Multi-vehicle Flexible Manufacturing Platform Technology for Future Smart Automotive Body Production.

The developed *ICP-Platform*, as an environment for the design and development of smart factories, is designed for the automated design of production systems with specified characteristics based on the aggregation of the initial data of the enterprise, while the relationships and rules between the data are built in the most effective way according to the principle of increasing the flow rate.

At the same time, in the task of designing a new production system, both production and economic characteristics can be considered. The analysis of these parameters allows you to find limitations and eliminate them, justify investments, and predict the timing of production plans.

The developed *ICP-Platform*, as an environment for the design and development of smart factories, is designed for the automated design of production systems with specified characteristics based on the aggregation of the initial data of the enterprise, while the relationships and rules between the data are built in the most effective way according to the principle of increasing the flow rate.

The ICP-Platform consists of separate service applications that provide the ability to implement the specified functionality. In this paper, AnyLogic and BFG-IS software products are considered as the main modules.

The AnyLogic (https://www.anylogic.com/) *modeling and simulation environment* supports the design, development, documentation of the model, and execution of computer experiments with the model, including various types of analysis — from sensitivity analysis to optimization of model parameters relative to a certain criterion.

The BFG IS (https://bfg.ai/) *modeling and simulation environment* is a production planning system that manages production flows in real time, schedules resources, dispatches deviations, and helps make decisions to eliminate them. The BFG IS modeling environment allows you to simulate real production enterprises, the logic of setting up and entering source data is subordinated to the logic of starting a real enterprise.

The process of designing a new production system included the following steps:

1) Creating models of the production system.

2) Analyzing opportunities and limitations.

3) Synthesis of alternatives to the production system to achieve the set goals.

4) Selecting and comparing alternatives for changing the production system.

The source data is intended to describe what an enterprise can do and what resources it has to do it. This includes information about the product range and composition, its production technology, and information about technical and human resources in relation to the organizational structure, which is necessary for conducting simulation. In this case, the initial data for the design are the following documents: the composition of the products (specifications), production technology (extended description of route technological processes with production and preparatory and final times), production capacity in relation to the organizational structure (equipment, personnel, equipment), production plan, economic data.

There are two possible ways to set the source data:

1) The description of the production model is collected in a single file-an Excel workbook with a set of consecutive tabs that have a strictly fixed name and order.

2) The description of the production model is a set of separate files (format .xls or .csv), where each file describes a separate part of the production model.

Fig. 3 shows a simulation model of the experimental Smart Factory developed in the AnyLogic module. This module reflects the prototype of the technological process for the production of permanent magnets. The process includes the preparation of raw materials, primary mixing, manufacturing of the reinforcing structure, the introduction of the reinforcing structure into the composition of the composite material of the workpiece, dosing, molding, and magnetization of the workpiece. At the end of the process, we get the finished product – a permanent magnet with the specified functional properties.

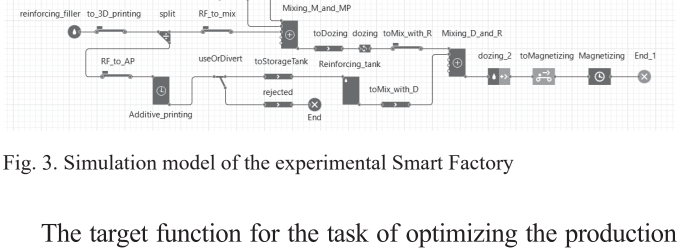

Fig. 3. Simulation model of the experimental Smart Factory

The target function for the task of optimizing the production system is the minimum production time with maximum productivity of the entire order portfolio. The platform provides real-time management of production flows, schedules resources, dispatches deviations, and helps make decisions to eliminate them. At the same time, the platform provides forecasting of the consequences of decisions made when planning production programs and allows to manage changes in the production system.

V. Discussion

The results of the Smart Factory design, modelling, and simulation process shows

In this work authors developed and proposed an application of SOA for experimental Smart Factory based on KSTU. The experimental factory has been designed to produce magnetic materials.

At a first stage of the research the "AS IS" state of the experimental factory was evaluated and analyzed. Based on the analysis and evaluation result the ICP-Platform modules were selected and configured.

A prototype (digital model) of a of the experimental factory has been developed. The prototype served as a model for production system simulation. At this stage of the research, the production system minimum valuable prototype (MVP) was used to confirm the functionality of the proposed System Architecture. The simulation results show the possibility of using the developed configuration of ICP-Platform for Smart Factory design. However, there is a need to refine the input parameters of the factory model, as well as to take into account the feedback loops.

Thus, the possibility of applying the proposed System Architecture requires further research. The current results of the development of the experimental Smart Factory project show potential opportunities for improving this project through further expanding the prototype functionality and its simulation in physical and virtual test environments.

IV. Conclusion

In this paper, the possibilities of using a service-oriented approach for designing the architecture of production systems were considered. The issues of designing the system architecture of the production system were studied on the example of the experimental Smart Factory. The application of the V-model as a system engineering tool for Smart Factory design is presented and described. The use of simulation and simulation technologies for the implementation of the Smart Factory concept is shown.

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