Multiscale Modeling and Simulation for Industrial Cyber-Physical Systems

Natalia Demkovich, Eugeny Yablochnikov
Dept. of Instrumentation Technologies
ITMO University
Saint Petersburg, Russia
ndemkovich@corp.ifmo.ru

Grigory Abaev
Head of technical support, PLM dept.
Bee Pitron SP, Ltd.
Saint Petersburg, Russia
age@beepitron.com

***Abstract*—The article deals with the creation and application of virtual ICPS objects. Ensuring flexibility of the production system and, accordingly, its timely reconfiguration requires the preparation of numerous technological and production parameters, which are formed on the basis of modeling at various levels – from a single technological operation to the production system as a whole. The article gives practical examples of creating virtual ICPS objects, shows both vertical links between modeling levels and their horizontal linkages with related technologies and real-world objects.**

Keywords*—digital manufacturing, simulation, Industrie 4.0, digital twin

I. Introduction

Industrial Cyber-Physical System (ICPS) is a network of interacting physical and data components designed as an unified system, which is arranged within the framework of the integrated reference (single basic) model of the production system and adaptable to real-world changes. One of the promising approaches for ICPS implementation involves usage of the multi-agent systems [1]. ICPS can be represented in 3 levels: (1) the level of physical objects capable of communicating with each other and adapting to the actual operating conditions of the ICPS; (2) the level of virtual data created and stored in a dynamic information network created on the basis of cloud technologies. Such data include 3D models, simulation dates, digital technological processes, numerous documents, these data are created using PLM-technologies; (3) the level that connects virtual and physical objects using numerous algorithms and services and ensures the functioning of ICPS [2].

The other key technologies and trends of the "Digital Manufacturing" are:

- IoT (Internet of Things) – extension of the industrial Internet, which allows to arrange the industrial networks for the equipment (M2M – Machine to Machine) and human (M2H – Machine to Human) integration.
- Big Data + B. I. (Business Intelligence) – possibility to store and process large volumes of real-time data incoming from the industrial equipment. Structured and marked data serve as the basis for training an intellectual model capable of predictive analytics.
- Automated production processes management systems: SCADA (Supervisory Control And Data Acquisition), DCS (Distributed Control System) and MES/MOM (Manufacturing Execution System / Manufacturing Operation Management). This class of systems has been known since the mid-to-late of XX century [3]. Then it included hardware and software systems designed for data collection (SCADA), production processes control (Manufacturing Execution System – MES) and enterprise resource management (ERP). The advances in information technology, including the above-described IoT and Big Data technologies, led to further development of these systems.
- Mechatronics – steady increasing of quantity of the mechatronic devices and software components in each individual device.
- Deep system integration, which involves "system of systems" development. The "system of systems" components in case of production system are represented by flexible manufacturing cells, which have a modular architecture and are equipped with network infrastructure, mobile robots and industrial cyber-physical systems.
- Augmented Reality (AR) and Virtual Reality (VR) – technologies, in which visualizers (AR/VR glasses, mobile pads and smartphones) are used for augmentation of real production facilities with data incoming to SCADA-system from the sensors and controllers installed directly on the equipment. The tecnology is used for checking of the key equipment operation parameters and ensuring continuity of the production process, and also for arrangement of access to the documentation via visualization of product documentation to assembly, mounting or maintenance directly at the production facilities.
- SOA (Service-Oriented Architecture) – interaction arrangement method used in multi-agent systems, which is based on services provided by individual agents in the common environment. Each service has a known cost, may be fulfilled within the known timeline, and is described by number of additional characteristics and parameters. Based on this information, the system

978-1-5386-6531-2/18/$31.00 ©2018 IEEE

makes the decision which agent will be selected for a particular task [4]. For instance, currently the described approach is used for interaction arrangement within the supply chain [5]. The problems of SOA application within the context of production and multi-agent ICPS are discussed in [6].

The above-mentioned technologies are pertinent to the stage of production systems operation including data exchange between devices and systems, processing of these data, sub-systems integration into global systems, visualization technologies, etc. However, similarly to the classical production systems, digital production systems (full or partly equipped with the listed technologies) require designing and modeling of functional, logic and information processes. It is ensured by application of PLM concept which includes such classes of computer systems as CAD/CAM (Computer Aided Design/Computer Aided Manufacturing), CAE (Computer Aided Engineering), CAPP (Computer Aided Process Planning), industrial robots programming systems, manufacturing processes simulation modeling systems and systems for ergonomics analysis of production processes and products maintenance, i.e. was attributed to the simulation field. The modern design systems are evolving pursuant to the progressive trends of technologies development, providing the respective modeling tools for solving designing and modeling tasks, ranging from the advanced tools for 3D modeling up to tools for engineering analysis, system engineering and digital manufacturing.

Next, several modeling levels of the production systems and processes will be presented; possibilities of usage of the obtained models in connection with the above-mentioned technologies will be discussed. The joint usage of the described models and technologies could lead to synergy, thus increasing the effectivity of the programs designed for creation of the factories based on the above-mentioned technologies.

All models presented in the article (Figures 1, 2, 3) were prepared by graduate students and undergraduates of the Department of Instrumentation Technology ITMO under the guidance of the authors of the article.

II. Multiscale Modeling of Production Systems

The production system is represented by a set of process components (human resources, equipment, conveyors, tooling), material and data flows within the framework of one enterprise. The person interacts with the production system through the M2H interface. During development of the simulation model, the production system may be considered on three levels:

- manufacturing operation level;
- manufacturing process level;
- production process level.

Manufacturing process involves changing of the parts', stocks' or raw materials' state via consequent fulfillment of manufacturing operations. Generally, more than one manufacturing processes are implemented at the enterprise (depending on the type of production and variety of products). The products manufactured at the enterprise (components of the compound devices) are forwarded to the assembly lines, where the assembly manufacturing processes are realized. Manufacturing process model includes all manufacturing operations, both the primary ones (which are related to changes in shape and properties of the stock material), as well as the supporting operations (control, transportation, etc.).

Production process model, along with the primary manufacturing processes which are directly connected with obtaining of the final products, includes supporting processes involving transformation of different types of the physical and information resources into the products and related services. These include supply chain, warehouses and human resources management and others.

It is worthwhile to say that the described multilevel model of the production process structure belongs, in turn, to the more complex ecosystem, which may be described using Reference Architectural Model Industrie 4.0 [7].

A. *Manufacturing Operation Level*

Modeling at the manufacturing operation level covers the shape or properties changing of the stock material, involving machining operation (turning, milling and others), forming operations (die stamping, forging), heat treatment, casting, injection molding and others.

Information on the properties of the raw material, on product, equipment and tooling design characteristics and on preliminary chosen process parameters is used as the initial data. Modeling is realized using CAE-systems based on finite element method, finite difference method, etc.

The simulation model of a manufacturing operation can be used to solve the following problems [8]:

- verification of the design manufacturability;
- planning of the product's manufacturing process – selection of manufacturing regimes for each specific operation;
- tooling design and manufacturing;
- production cost estimation.

Simulation of the manufacturing processes and separate manufacturing operations helps reveal and solve the potential problems at the early production stages and prevent manufacturing defects.

For a variety of modern manufacturing processes, such as additive technologies, composites processing and others, the cross-effect of the manufacturing process parameters on the properties of the final product is well-defined [9]. In such a case the product model, in which microstructure created during the product manufacturing is taken into account, is developed simultaneously with the manufacturing operation model, while the modeling process becomes iterative.

An important result of the simulation is the estimation of time required for the manufacturing operation fulfillment. These data are used for development of a second-level model, i.e. the model of a manufacturing cell.

As an example, let us consider a multi-level model of an instrument-making plant that produces instruments with polymeric optical elements.

Production of optical devices involves such manufacturing processes as machining operation, polymeric materials injection molding and assembly. Let us consider the model of thermoplastic polymeric material injection molding at the manufacturing operation level [10].

The injection molding process involves the stages of the injection mold filling with the molten material, packing under pressure, cooling and extraction of the part from the injection mold. All these stages are reflected in the process model (fig. 1), which has been developed using Moldex3D (CoreTech System, Ltd.).

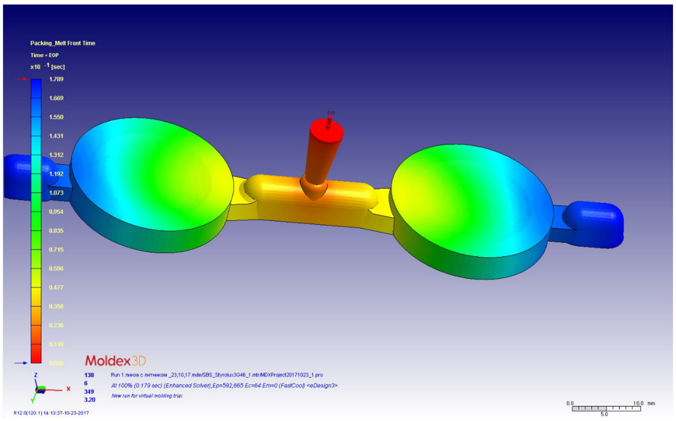

Fig. 1. Packing time (as displayed in Moldex3D)

Information on rheological and thermomechanical properties of the polymeric material, geometry of the mold cavity and location of the injection points, cooling system, manufacturing process parameters (temperature, pressure and others) was used as the initial data.

The result of the simulation was the following types of data:

- temperature distribution within the product design;
- residual stresses values;
- availability of pores in the material;
- availability and location of weld lines.

The results of modeling at manufacturing operation level were used for selection of the manufacturing parameters providing the best product's quality. Among the variable parameters were the injection time, packing time and mold opening time.

Time of the molding cycle fulfillment determined using the computational model was used for development of the simulation model of the automated robotized polymeric materials injection molding shop.

B. Manufacturing Process Level

At the manufacturing process level, a set of processes of changing the shape of the workpiece during the manufacture of the product or changing the product composition during the assembly or disassembly operations is modeled. Also at this level, the modeling of the operation of automated lines and sections is carried out, where the technological process is realized completely within the framework of a single production cell, consisting of various technological modules (processing, transport, assembly, etc.).

Information on the selected production technology (in the form of process routes), on the manufacturing parameters obtained at the stage of manufacturing operational level, on the geometrical constraints of the manufacturing areas where the equipment is located or should be located, on the equipment configuration within the manufacturing area, as well as on 3D models of the definite machine tools and production tooling, robots and other automation and mechanization facilities was used as the initial data for modeling.

Application of the manufacturing process model allows to solve the following problems:

- programming of individual automation equipment for performing specified operations within the framework of primary or supporting processes;
- determining of the operations duration for the automation equipment taking into account control programs;
- synchronization of the conjointly operating facilities at the level of virtual controllers and logical sequences of signals and variables that start or stop the execution of predefined programs;
- calculation of work-cycles time for the automated cells and equipment involved in manufacturing process;
- optimization of the cycles time for the automated production lines;
- performance calculation for the process system elements.

Thus, development of the manufacturing process level models allows not only to obtain control programs for devices and to master algorithms of their interaction in the virtual environment within the manufacturing process framework, but also to obtain the data necessary for economic analysis of any given organizational decision and in some cases even the data for the production planning, in-house logistics and sales planning departments.

As an example, consider the simulation model of the automated robotized molding shop for polymers injection molding, which is shown in Fig. 2. Fig. 2 shows the 3D model of the production line, the linear model of the manufacturing process and the Gant diagram with the data on the time rationing of the process.

DELMIA 3DEXPERIENCE was used for development of the manufacturing cell simulation model. The detailed description of the model was given by the authors in [11].

At the first stage of simulation modeling the virtual controllers for each executive device presented in 3D model have been defined. Then a connection was arranged between the virtual controllers at the level of input and output signals, which are sent between the devices and which provide the joint interaction during fulfillment of the manufacturing cell process simulation modeling.

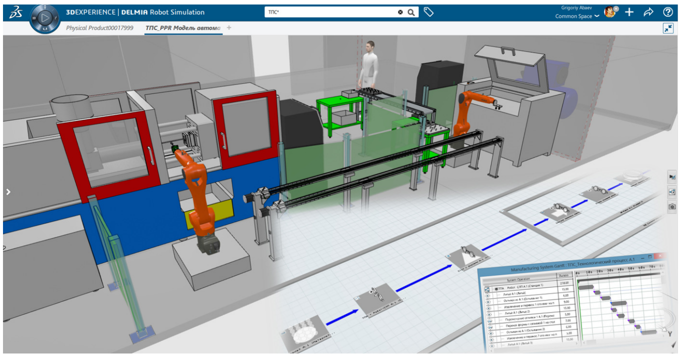

Fig. 2. Manufacturing cell & process model with the Gantt chart (as displayed in DELMIA 3DEXPERIENCE)

Next, primary and supporting operations (tasks) for the individual devices were simulated, such as polymer molding, extraction from the mold and transportation by robots, processing on the laser cutting machine (in order to remove the pouring gate system), conveyer transportation, etc. To ensure synchronous operation and timely execution of tasks by several devices, variables were introduced into the program of each individual task, initiating or stopping the movement of actuators.

At the second stage, a general model of the technological process was developed to calculate the productivity of the robotized area with the use of tools for the simulation of manufacturing processes of DELMIA 3DEXPERIENCE. The time parameters of the technological operations and cycles were obtained by modeling the casting process in the CAE system at the manufacturing operation level.

As a result of modeling, the following data were received:

- four-dimensional (3D + time) model of the automated shop for polymer molding;
- control programs for the industrial robots;
- equipment interaction algorithm;
- technological tooling models;
- optimization of the production cycle time;
- capacity calculation for the automated molding shop.

The received data for the individual manufacturing cells, automated workcenters and manufacturing lines serve as the basis for modeling production processes at the inter-shop level.

C. Production Process Level

Models of the next level – production process level – take into account inter-shop cooperation and logistics, global and local storage systems and combine multiple manufacturing processes implemented at the enterprise into a single digital model of the production process. Such models represent the level of a virtual factory and, at the moment, are most in demand for design tasks of production systems from scratch or complex modernization of existing workshops and sites (equipment installation and layouts designing, geometrical calculations in context of designing of operations pertinent to relocation of the large-size equipment). These digital models may reach the plant scale and at the same time contain in their structure the models of the previous level – individual shops and/or automated production lines – in order to calculate their capacity within the framework of general production process, and optimize the load taking into account the results of the capacity and workload calculation fulfilled for the adjacent (simultaneously operated) shops.

For the manufacturing enterprise, which model is shown in Fig. 3, such an approach is of immediate interest for the workload optimization of the machining department providing the workload of the assembly department, with due account of capacities of the simultaneously operated manufacturing processes and potential assembly processes. Such synchronization of the processes allows to minimize the stock reserves of semi-finished products, to reduce quantity or capacity of the buffer storage systems and possibly to realize the necessity of increasing of the production resources for the definite processes with the aim of general capacity increasing and bottlenecks elimination.

It should be noted that such models make it possible to present in more details both the manufacturing processes (manufacturing process level), as well as the aspects of Building Information Modeling (BIM), i.e. models, which are reflecting the design features of the plant, stages of construction and necessary construction equipment and which are incorporating the data pertinent to various engineering and informational communication lines, electric mains and power systems, hydraulic systems for technical fluids and industrial gas delivery to the manufacturing equipment, information models, which are describing data exchange between the computer systems, equipment, humans, etc. Meanwhile, one model allows to realize simultaneously several information layers, namely:

- 2D layer (layout);
- 3D layer;
- engineering systems layer;
- informational flows functional and logical layer (functional and logical diagrams of informational flows and logical interfaces connectivity);
- manufacturing processes layer (routes, simulations);
- plant construction process layer (BIM).

As an example, the model of instrument-making plant is considered (Fig. 3), which was designed for solving of rather simple tasks (as we may judge based on the contemporary knowledge), namely:

- search of bottlenecks in the process routes with due account of the available and scheduled for purchasing equipment;
- visualization of the general design concepts;

- optimization of the local storage systems located in zones between the manufacturing shops and directly nearby the automated cells of "robot-machine unit" type.

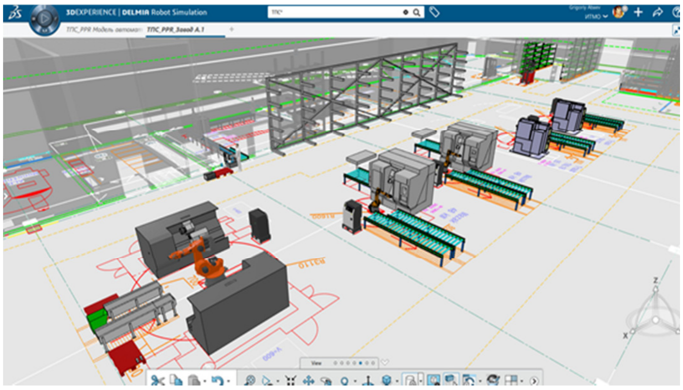

Fig. 3. Production process level model of a plant (machine shop – as displayed in DELMIA 3DEXPERIENCE)

The initial data for modeling were as follows:

- technological layout of workshops and sites (2D-layout);
- process routes presented in the form of Excel spreadsheets and including information on the labor intensity of operations;
- BOM-specification for the product manufactured by the plant.

The results of modeling are as follows:

- multiscale 3D model of the plant has been developed;
- the bottleneck in manufacturing process has been revealed and eliminated via usage of the additional equipment; the manufacturing process capacity has been calculated with due account of the scheduled production volume and working shifts duration;
- quantity of the buffer warehouses has been reduced;
- the fundamental decision has been adopted on changing and redesigning of the whole machining workshop and introducing of integrated automation and robotization into the production process.

III. Building a Digital Twin

The technology binding the object's digital model and the real-world object is called "Digital Twin". The authors propose the following definition of this technology in the field of industrial production:

A digital twin of a production system is a multi-level digital layout that describes the product, processes and resources in the environment of their functioning, i.e. allowing to simulate the processes taking place in the real system, as well as collecting and displaying in real time data on the status of objects obtained from the PLC and sensors installed in the production system both on industrial equipment and in its environment.

The implementation of this model is carried out using IoT and Big Data technologies in building communications, collecting and analyzing data coming from sensors and controllers installed on industrial equipment [12]. It stands to mention the existence of prospects in the field of solving communication problems between the Digital Twin and a real-world object, connected with the integration into PLM solutions of such packages as Modelica/Dymola [13], Matlab/Simulink, which will allow not only to develop binding between the real-world and digital objects, but via usage of special libraries (for instance, such libraries as "TrueTime" and "Modelica EmbeddedSystems") to describe real communication problems, such as communication delays, signal limitations, measurement noise and many other things, which ultimately should provide the most precise coincidence between the model and the real process.

Digital Twin is used for the following three purposes:

- remote monitoring of the real-world object's state via displaying the parameters of its operation on the digital model and indicating the units and equipment parts which operating parameter values deviate from the normal ones, as well as arrangement of the predictive servicing system via analysis of large volumes of the statistical data pertinent to the equipment operation during the considered period (Big Data analysis);
- remote object control via the digital model (control signals transmission from the digital model to the real-world object);
- native programming of the industrial collaborative robots (cobots) – the man routinely (manually) controls robots, moving the real-world object along the route that is necessary for fulfillment of the manufacturing operation, while the digital model simultaneously records these actions, hence generating the program for its rerun.

The last item is very important since it directly brings us to the matters of machine learning of the automated production systems. In context of contemporary programs of industry modernization (Industrie 4.0 , Advanced Manufacturing, National Technology Initiative and others) the task of self-teaching of ICPS is even more challenging [14], and therefore our above-presented definition of the Digital Twin should be supplemented by the following paragraph:

Such a digital model can generate large amounts of data that are processed for the purpose of machine learning. The system of machine learning also receives statistical data on the quality of products. After training, the system becomes capable of forecasting and preventing production costs associated with the scrap and failure of the production equipment, including by conducting high-precision, high-performance modeling and statistical analysis of its results.

In the context of the digital production paradigm, the models of manufacturing operational level serve to conduct a variety of virtual experiments, the results of which, in combination with data pertinent to defective products and with the results of real-world experiments may serve as a statistical basis for ICPS training in terms of quality. Nowadays these models already allow reducing quantity of the full-scale experiments. An example is the automotive industry, where the number of full-scale crash tests has already significantly decreased due to the use of virtual ones.

The manufacturing process level models (individual equipment, shops and process lines) serve for displaying of data and states of the manufacturing equipment, signal detection from the probes and signal transfer to PLC. Consequently, they are the necessary and sufficient models, capable at the expense of creating communications, to become the digital basis for the Digital Twins arrangement.

At the existing stage of development and implementation of the described processes, designing of the detailed global models of the plants (at the production process level) seems to be excessive, while arrangement of the Digital Twin for the whole plant seems to be inexpedient due to the large demands on computation power and substantial manpower effort for its detailed development, provided there is no clear understanding of the scope of their further application directly in production itself, with the exception of monitoring tasks. However, with the development of the CPS area, and in particular ICPS, similar models can serve as an interactive map reflecting the state of all objects and storing accurate information about the geometric arrangement of objects. Such maps may be used for arrangement of the autonomous mobile robots interaction system via SOA, serve as a field for extending the IoT area to the digital world of 3D models, to be sources of data for Augmented Reality Devices and to perform other functions for connecting the digital world with the real one for solving production problems.

IV. Conclusions

The authors' experience in the use of modeling systems makes it possible to note the high effort required for development of accurate models of standard production systems, such as industrial machines, robot machining systems such as "robot - machine" and some others. This is due to the lack of standard libraries of 3D models of industrial equipment or a commercial trading platform for 3D models, where one could purchase a 3D model of equipment facilitated in terms of commercial information directly from its manufacturer, observing the legal purity of using such models.

The carried-out complex of researches allowed to create a complex of virtual objects, processes and production resources for studying and working out various aspects of ICPS design. Currently the authors are engaged in study of methodological principles of the Digital Twins arrangement, which includes detection of the set of controlled variables (signals), their classification with revealing of functional (which exert an effect on quality, capacity, etc., i.e. which are attributed to estimation characteristics of the real-world system activity) and auxiliary variables (which are necessary for transmission to the digital model for the Digital Twin arrangement), as well as revealing interrelations between them.

Further research will be directed to the organization of communication between the real-world industrial object and its digital model. This connection involves the exchange of signals between the real and virtual controllers at the input / output level of these devices. Such a connection is supposed to be carried out through the Modelica / Dymola toolbox within the 3DEXPERIENCE digital platform. In this case, the virtual controller at the first stage controls the digital model, while the real-world PLC controls the real-world object(s). After communication adjustment, it is expected that the real-world controller's software debugging using the digital model will become possible.

References

[1] Paulo Leitao, Stamatis Karnouskos, Luis Ribeiro, Jay Lee, Thomas Strasser and Armando W. Colombo, “Smart Agents in Industrial Cyber-Physical Systems”, 2016, Proceedings of the IEEE, (104), 5, 1086-1101. http://dx.doi.org/10.1109/JPROC.2016.2521931.

[2] C. Manzei, L. Schleupner and R. Heinze, Industrie 4.0 im internationalen Kontext. Berlin: VDE VERLAG, 2017.

[3] W. Shaw, Cybersecurity for SCADA Systems. PennWell Books, 2006. ISBN: 978-1593700683

[4] M. Cao, R. Ch, Y. Liu, “Developing a multi-agent automated negotiation service based on service-oriented architecture”, Service Science, vol. 1, No 1, pp. 31-42, 2009.

[5] S. Srinivasan, S. Kumar Singh and V. Kumar, "Multiagent system based service oriented architecture for supply chain management system MAS-SOA-SCM", International Journal of Computer Applications, vol. 27, no. 5, pp. 12-17, 2011.

[6] A. Colombo, T. Bangemann, S. Karnouskos, J. Delsing, P. Stluka, R. Harrison, F. Jammes and J. Lastra, Industrial Cloud-Based Cyber-Physical Systems. Cham: Springer International Publishing, 2014. DOI: 10.1007/978-3-319-05624-1

[7] ZVEI - German Electrical and Electronic Manufacturers’ Association, "Industrie 4.0: the Reference Architectural Model Industrie 4.0 (RAMI 4.0)", 2015.

[8] K. Chang, Product Manufacturing and Cost Estimating Using CAD/CAE. EU: Elsevier Inc., 2014.

[9] N. Demkovich, I. Volkov and E. Yablochnikov, "Numerical simulation in implementation of new manufacturing technologies", Izvestija Samarskogo nauchnogo centra Rossijskoj akademii nauk, vol. 18, no. 3-4, pp. 459-463, 2016.

[10] E. Yablochnikov, A. Pirogov, S. Vasilkov, Y. Andreev and N. Demkovich, "Developing and modeling production processes for manufacturing polymeric optical items in a distributed integrated medium", Journal of Optical Technology, vol. 84, no. 1, p. 62, 2017. DOI: 10.1364/JOT.84.000062

[11] G. Abaev, N. Demkovich and E. Yablochnikov, "Role and issues of simulation during the transition phase to digital manufacturing and “smart factories", Proceedings from IMMOD-2017, St. Petersburg, 2017, pp. 219-227.

[12] J. Tolujew, "Simulation tasks during the implementation of the Industry 4.0 concept in the field of production and logistics", Proceedings from IMMOD-2017, St. Petersburg, 2017, pp. 57-65.

[13] D. Henriksson and H. Elmqvist, "Cyber-Physical systems modeling and simulation with Modelica", Proceedings from the 8th International Modelica Conference, Technical University, Dresden, Germany, 2011.

[14] J. Lee, B. Bagheri and H. Kao, "A Cyber-Physical Systems architecture for Industry 4.0 -based manufacturing systems", Manufacturing Letters, vol. 3, pp. 18-23, 2015.