The Next Stage of Industry 4.0: From Cognitive to Collaborative and Understanding Agents

Valery B. Tarassov
Bauman Moscow State Technical University
Moscow, Russia
Vbulbov@yahoo.com

***Abstract*—The paper considers the role of artificial cognitive, collaborative and understanding agents in developing Industry 4.0 initiative. Primarily, a proposal of using both open semantic and pragmatic intelligent technologies for Industry4.0 is justified. The evolution of Industry 3.0 and the first International Program on Intelligent Manufacturing Systems are analyzed as forerunners of Industry 4.0. Some basic ideas and principles of Industry 4.0 are clarified, its enabling technologies are presented. The thesis about enterprise total agentification is formulated. A possible solution of the problem how to construct artificial understanding agents is suggested. Finally, three basic ways of developing new generation technologies for Industry 4.0 are discussed**

***Keywords*—Artificial Intelligence; Intelligent Agent; Industry 4.0; Cyberphysical System; Internet of Things; Collaborative Robot; Enterprise Agentification**

I. INTRODUCTION

Nowadays the worldwide initiative called Industry 4.0 [1-5] becomes a main challenge for developing open advanced semantic and pragmatic technologies in modern Artificial Intelligence. An important justification for the relevance of this thesis is the organization of the First International Conference on Industry 4.0 and AI technologies; it will be held in August 2019 at Cambridge University, United Kingdom. Among its hot problems such topics as AI-based hardware, virtual agents, clustering, machine learning, deep learning platforms, evolutionary computations, speech recognition, natural language generation, knowledge representation and reasoning, text analytics, intelligent simulation and robotics, data interpretation and analysis, including graph and network approaches to data mining, are mentioned.

In Russia the First Workshop «Industry 4.0 Strategy, Internet of Things and Ambient Intelligence» took place at the conference «Intelligent Systems and Computer-Integrated Manufacturing», which was organized jointly by Bauman Moscow State Technical University and Russian Association for Artificial Intelligence in January 25-26, 2019. Below we will tend to establish some links between technologies of Industry 4.0 and OSTIS project.

The OSTIS project [6,7] has been initiated in order to develop open semantic technologies of designing intelligent systems. We suggest its complementation by outlining open pragmatic technologies for intelligent agents, rising to the ideas of the «Father of Pragmatism» Ch.S.Peirce [8].

Let us point out that in information theory and semiotics a clear difference between semantics and pragmatics is made. Semantics expresses the relation between message and its author or sender, whereas pragmatics considers the value of message for its user in the context of his goal achievement. By taking pragmatics rules, we cope with many-valued or even uncertainty-valued (the term coined by V.V.Martynov [9,10]) reality of natural language and select some current value – the basic one for a given time. To differ from semantics which has no addressee, pragmatics takes into account such a special addressee – interpreter. These considerations are quite relevant while building intelligent technologies for Industry 4.0.

The aim of the paper consists in reviewing the-state-of-the-art in modern technologies for Industry 4.0, as well as analyzing new intelligent, cognitive, social approaches to implement NBICS convergence concept [11] for the next stage of Industry 4.0.

Primarily, the difference between Industry 3.0 and Industry 4.0 is discussed, and the shift from pure manufacturing to a family of info-communication industrial technologies for digital, virtual, smart enterprises is shown. Then nine basic components of Industry 4.0 are considered, including Cyberphysical Systems and Internet of Things, Big Data Analytics and Cloud Technologies, Intelligent Simulation, Augmented Reality and Collaborative Robots. Finally, the problem of total enterprise agentification based on both physical and virtual artificial agents able to «understand» required behavior patterns in a specific industrial situation is faced.

II. WHAT IS INDUSTRY 3.0?

A. Evolution of Industrial Revolutions: Four Big Jumps

The sequence of industrial revolutions is shown in Figure 1 (see [12]). The First Industrial Revolution (Industry 1.0) was deployed in XVIII-XIX centuries (more exactly, between 1760 and 1820) and could be viewed as the dawn of industrialization. There was the transition from handcraft to machine-based human work, from agrarian and rural to mainly industrial and urban society. The iron and textile industries were its locomotives; basic symbols were water power, steam engines, mechanization through spinning mills.

The Second Industrial Revolution, which is also called the Technological Revolution (Industry 2.0), took place between 1870 and 1914, just before World War I. It was a period of rapid industrialization, including both the growth of pre-existing industries and expansion of new ones, such as steel, oil and electricity. The electric power was used to create the mass production.

Advances in manufacturing and production technology enabled the widespread adoption of technological systems such as telegraph and railroad networks. The XX^{th} century symbols of Industry 2.0 were early factory electrification and the assembly lines (first of all, automobile production lines of Henry Ford).

The Third Industrial Revolution in the last third of XX century was the introduction of electronics, computers and automation in manufacturing. So a big industrial robot for assembly was selected as its typical face.

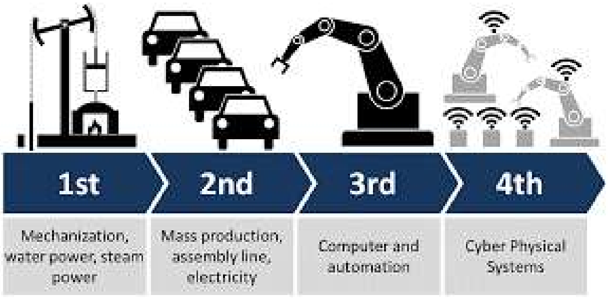

Figure 1. Symbolic Representation of Four Consequent Industrial Revolutions

While Industry 3.0 faces the problem of automating single machines and technological processes with using computers and electronic devices, Industry 4.0 focuses on the end-to-end digitization of all physical assets and their integration into digital ecosystems with value chain partners. Digitization means the process of converting information in a digital form; the result is called digital representation. Here the keyword is «Ubiquitous Digitization», i.e. digitization and integration of both vertical and horizontal value chains, digitization of product and service offerings, digitization of business models and customer access, and so on.

In a wide sense, Industry 4.0 encompasses both a new industrial enterprise vision and its keynote mission in the age of digital economy. The basic principle of Industry 4.0 states: by connecting machines, work pieces and systems, businesses are creating intelligent networks along the entire value chain that can control each other autonomously.

To show necessary prerequisites for Industry 4.0, let us consider the evolution of Industry 3.0 technologies.

B. On Basic Steps of Industry 3.0.

Manufacturing systems in the era of mass production were based on homogeneous *automated lines* operating in a stable, well-defined environment. *Flexible technological modules* are heterogeneous and more efficient; they include machines, instruments, manipulators and robotic systems.

The arrival of *Flexible Manufacturing Systems* (FMS) means a further increase of complexity. All the components of flexible modules are present; besides, automated storage and retrieval systems, transportation systems, planning and control systems, local computer network, and other tools are included. Here FMS are good examples of complex, heterogeneous, highly integrated systems with different subsystems. In particular, flexible technological subsystems, flexible transport subsystems, flexible measurement-information subsystems are worth mentioning. Various robots equipped with their own computer systems can also be viewed as technological modules. For instance, transportation robots, welding or assembly robots, stackers-robots are widely used in FMS. A typical example of educational-training Denford FMS is given in Figure 2.

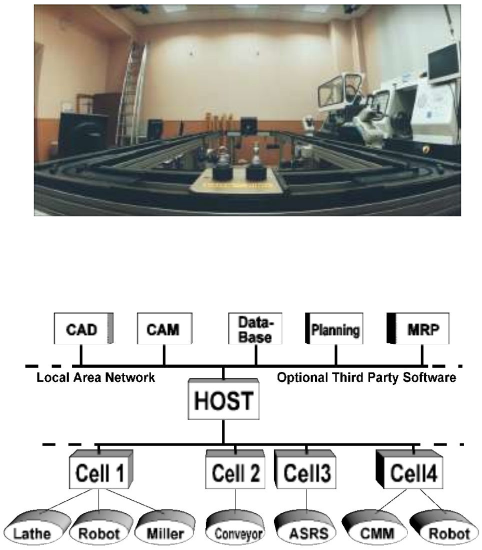

Figure 2. Outward Appearance and Architecture of Denford FMS

A flexibility of complex system means its capacity of rapidly react to environment changes and quickly adapt to these changes. In case of manufacturing system the flexibility supposes the capacity to quickly adjust without considerable expenses both to make new or modernized products and introduce new technological processes with new equipment.

The concept of *Computer-Integrated Manufacturing* (CIM) concerns such complex industrial systems as job-shop, enterprise, network of enterprises, where all operations with information flows for all the phases of manufacturing are based on computer technologies [13]. It is worth noticing that CIM is more sophisticated system with respect to FMS. Apart FMS subsystems, it includes CAD/CAM/CAE system, PLM (Product Lifecycle Management), MRP II (Second Generation Manufacturing Resource Planning) standard, and so on.

Conventionally, CIM was viewed as a considerable part of product lifecycle from the expression of the need in this product to its launch to the market; the stage of product use was considered as an external one with respect to CIM. Later on, both complex product maintenance and its demolition became the trouble of its producer. In 1990's a new concept of CIM appears that encompasses all the product lifecycle, where the idea of lifecycle inversion after product demolition and inverted manufacturing realization is crucial [14].

Now it is clear that CIM supposes Enterprise Integration [15]. Moreover, the idea of *MetaCIM* as Computer-Integrated Manufacturing in Networked, Virtual, Computer-Integrated Enterprises has been suggested [16]. Thus, a multi-dimensional computer-based integration around the triple «product lifecycle–enterprise lifecycle–industrial knowledge lifecycle» has been considered.

The next natural step consists in organizing distributed manufacturing systems in virtual enterprises [17,18].

The evolution of Industry 3.0 production systems is depicted in Figure 3 (see [19]).

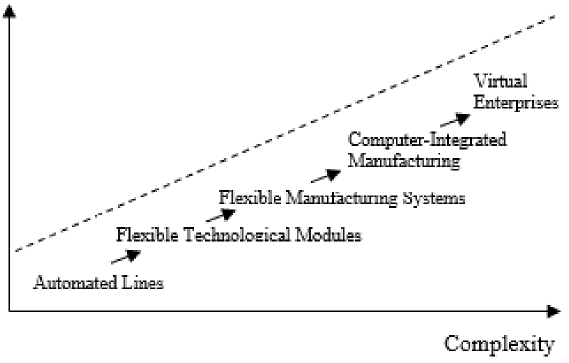

Figure 3. Evolution of Computer-Integrated Manufacturing Systems in XX Century

C. Intelligent Manufacturing Systems: First Results

The first step in making manufacturing intelligent was the International Program «*Intelligent Manufacturing Systems*» (IMS) which was started in the mid 1990's (see [20,21]). The objective of this program was the creation of new generation manufacturing systems and technologies by performing global intercontinental joint projects. These big projects, such as GLOBEMAN'21 (the abbreviation of Global Manufacturing in XXI century) [21], Next Generation Manufacturing Systems, GNOSIS, Holonic Manufacturing Systems faced many aspects of automated, integrated, intelligent manufacturing.

Primarily, the topics of IMS program were divided into five groups: 1) modeling and management of total product lifecycle; 2) analysis and development of production and business processes for enterprises of different industries; 3) enterprise strategy planning and engineering techniques and tools; 4) human, organizational, social factors of production; (5) virtual and extended enterprises.

Let us focus on GLOBEMAN'21 project. It was devoted to the problems of enterprise integration and product lifecycle modeling for global manufacturing in XXI century. The following results are worth analyzing [21]: a) design of direct and inverse product lifecycle management systems; b) creation of new technologies of intelligent simulation, decision support and production management for the enterprise networks; c) development of innovative CIM architectures in the enterprise networks to obtain world class products; d) remote customer service and support by using the information about real customers needs and real products manufactured by plants located in different parts of the world; e) more complete and deep understanding of new trends in manufacturing related to advanced information and communication technologies.

It is worth stressing that within the IMS program some basic knowledge engineering problems were faced and solved: (1) acquisition of manufacturing knowledge and experience; development of large and distributed knowledge bases; (2) data mining and knowledge discovery in manufacturing; (3) implementation of heavyweight ontological models for virtual enterprises (see ToVE project [22]); (4) creation of intelligent information technologies for production management; (5) design of innovative enterprises and manufacturing systems on the basis of Artificial Life approaches and bionic (swarm cognition) algorithms.

So GLOBEMAN'21 project was performed by an international consortium to develop and demonstrate the enterprise integration tools and methods. Its purpose was enabling manufacturing enterprise by new technologies to form a mission oriented project organization, i.e. a virtual corporation, for networked manufacturing business. Both industrial and university partners from various countries and even continents took part at the project. These partners formed virtual organization. It was an important step on the way to Industry 4.0.

Virtual organizations can be divided into virtual corporations and virtual partnerships. A virtual corporation is loosely coupled enterprise which is formed by many partners to fulfill a difficult mission requiring shared resources or organize world class production. Various examples of virtual partnerships can be bound in social networks, such as Twitter, Instagram, Linkedin.

III. INDUSTRY 4.0 AND ITS COMPONENTS

The term Industry 4.0) firstly appeared at Hannover Messe in 2011 as an outline of German industrial perspectives [1]. Nowadays the concept of Industry 4.0 has spread far beyond Germany and is widely used all over the world. The similar initiatives are called: *Industrial Internet* in the USA, *High Value Manufacturing Catapult* in the United Kingdom, *Usine du Futur* in France, *Fabbrica del Futuro* in Italy, *Smart Factory in Netherlands*, *Made Different* in Belgium, *Industrial Value Chain Initiative* in Japan, *Made in China 2025*, *National Technology Initiative* in Russia, and so on.

In 2015, McKinsey [23] defined Industry 4.0 as «the next phase in the digitization of the manufacturing sector, driven by four basic factors: a) an astonishing rise in data volumes, computational power and connectivity, in particular, low-power wide-area networks; b) the emergence of analytics and business-intelligence capabilities; c) new forms of human-machine interaction such as touch interfaces and augmented-reality systems; d) improvements in transferring digital instructions to the physical world, such as advanced robotics and 3D printing».

The most important idea of Industry 4.0 is the fusion of the physical and virtual worlds [1] provided by *Cyberphysical Systems* (CPhS) [1,24]. The emergence of CPhS means the inclusion of computational resources into physical-technical processes. In others words, embedded computers and networks monitor and control the physical-technical processes with feedback loops, where physical processes affect computations and vice versa. Within modular smart factories, physical processes are monitored, virtual copy of physical world is created, and well-timed decentralized decisions are made.

Let us note that CPhS are mechatronic systems enhanced by advanced tools of data/knowledge acquisition, control and communication. Their components continuously interact, providing CPhS self-adjustment and adaptation to changes. It is obvious that CPhS are crucial for production digitization. Here work pieces, devices, equipment, production plant and logistics components with embedded software are all talking to each other. Smart products know how they are made and what they will be used for. Thus, both production machines and equipment and products become cognitive agents involved into manufacturing and logistics processes.

A vision of smart factory as a system of CPhS is given in Figure 4.

There are five basic principles for implementing Industry 4.0: 1) Interconnection; 2) Information Transparency; 3) Total Interoperability; 4) Decentralized Decisions; 5) Technical Assistance. Here *Interconnection* is viewed as the ability of both people and machines, devices, sensors communicate with each other via the Internet of Services and Internet of Things. Interconnectivity supposes *Information Transparency*: it allows to collect immense amounts of data and information from all points in manufacturing processes and make more adequate decisions. *Decentralized Decisions* are tightly connected with CPhS, which are able to perform their tasks as autonomously as possible. Only in case of emergency decision-making is delegated to a higher level. *Technical Assistance* primarily concerns the simulation of manufacturing process in virtual world; more generally, it is the ability of artificial agents to support human agents, in particular, by performing unsafe, unpleasant or too exhausting tasks. *Total Interoperability* is understood as the ability of industrial system to work with other products and systems without any restrictions.

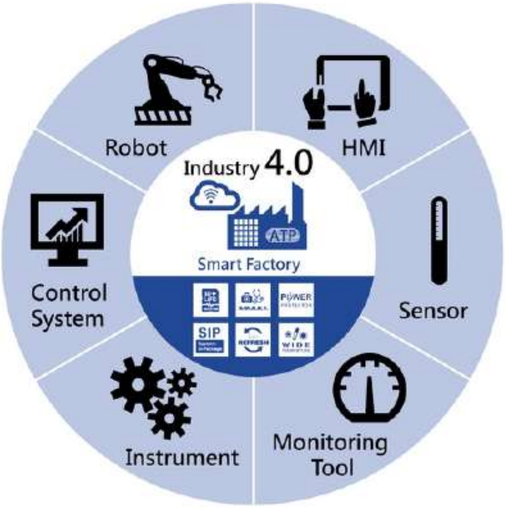

Figure 4. Basic Components of Smart Factory

Nowadays, BCG's nine basic technologies for Industry 4.0 are usually considered [25] (see Figure 5). Let us briefly analyze these technologies.

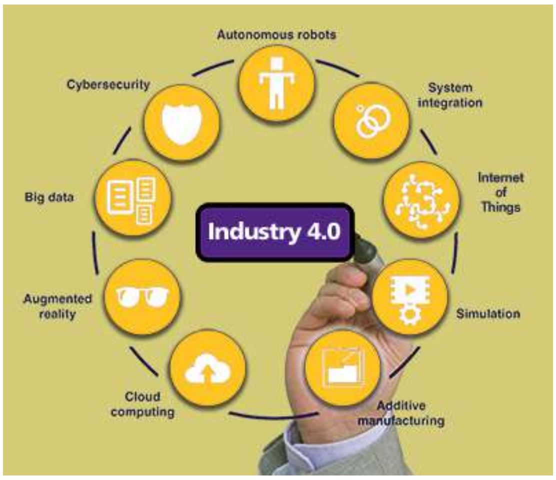

Figure 5. Nine Key Technologies for Industry 4.0 (by BCG)

A. Enterprise Integration and Engineering

The implementation of Industry 4.0 is closely related to enterprise engineering problems [26], in particular, strategic and ontological engineering [27]. With Industry 4.0, companies, departments, functions, and capabilities will become much more cohesive, as cross-company, universal data-integration networks evolve and enable truly automated value chains. Both horizontal and vertical enterprise integration takes place [3]. On the one hand, the initiative Industry 4.0 means digital representation and vertical integration of basic processes across the entire enterprise, from product development and purchasing, through manufacturing, logistics and service. On the other hand, horizontal integration goes beyond the internal enterprise operations by involving both suppliers and customers together with all other value chain partners. It includes technologies from track and trace devices to real time integrated planning with execution.

B. The Internet of Things

The Internet of Things (IoT) is a vision where every object in the world has the potential to connect to the Internet and provide their data so as to derive actionable insights on its own or through other connected objects. The Internet of Things allows people and things to be connected anytime, anyplace, with anything and anyone, ideally using any path/network and any service [28]. The appropriate technologies open new, wide opportunities for engineering networked enterprises.

The term «Internet of Things» was first coined by Kevin Ashton, the founder and head of Auto-ID Center in MIT, in 1999. As he stated, «the IoT has the potential to change the world, just as the Internet did – maybe even more so» [29]. It will comprise many billions of Internet-connected objects (ICOs) or «things» that can sense, communicate, compute, evaluate, interpret and potentially actuate, as well as have intelligence, multimodal interfaces and social ability.

Gartner defines IoT as «the network of physical objects that contain embedded technology to communicate and sense or interact with their internal states or the external environment» [30]. In [31] it is specified as a dynamic network of uniquely identified objects that communicate without human interaction by using IP. This infrastructure, possessing self-configurating capabilities, is based on standard and interoperable communication protocols, where physical and virtual things have identifiers and physical attributes, use intelligent interfaces and are tightly interconnected.

Nowadays, such communication and network technologies as IPv6, web-services, Radio Frequency IDentification (RFID) and high speed mobile 6G Internet networks are employed.

The IoT incorporates basic concepts from pervasive, ubiquitous, cognitive computing, which have been evolving since the late 1990's and have now reached some level of maturity.

Over the Internet of Things, cyber-physical systems communicate and cooperate with each other and with humans in real-time both internally and across organizational services offered and used by participants of the value chain.

The IoT is an enabler to many application domains including intelligent manufacturing, product lifecycle management, smart logistics and transportation, aerospace and automotive industries. Society-oriented applications of IoT include smart cities, smart buildings (both home and office), telecommunications, new generation media, smart grids, medical technology, collective and social robotics. Environment-focused applications include agriculture, breeding, recycling, environment monitoring and disaster alerting.

C. Cloud Computing

Cloud Computing [32,33] is a general term that refers to delivering computational services (servers, storage, databases, software, networking, analytics, etc.) over the Internet («the cloud»). It is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources that can be rapidly provisioned and released with minimal management effort or service provider interaction.

The NIST cloud model includes five basic characteristics, three service models and four deployment models. The following cloud characteristics are considered in [32]: 1) broad network access; 2) on-demand self-service; 3) resource pooling; 4) rapid elasticity; 5) measured service.

Here *broad network access* means that various capabilities are available over the network and accessed through standard mechanisms promoting the usage by heterogeneous thin or thick client platforms (e.g. mobile phones, tablets, laptops, and workstations).

In the context of *on-demand self-servic*, the consumer can unilaterally provision computing capabilities, such as server time and network storage, as needed automatically without requiring human interaction with each service provider.

Moreover, the computing *resources are pooled* to serve multiple consumers by using a multi-tenant model, with different physical and virtual resources dynamically assigned and reassigned according to consumer demand. There is a sense of location independence in that the customer generally has no control or knowledge over the exact location of the provided resources (storage, processing, memory, network bandwidth).

Besides, computing capabilities can be *elastically provisioned* and *released*, in some cases automatically, to scale rapidly outward and inward commensurate with demand. To the consumer, the capabilities available for provisioning often appear to be unlimited and can be appropriated in any quantity at any time.

Finally, resource usage can be monitored and reported, ensuring transparency for both the provider and consumer of the utilized service.

Three service models are: a) Software as a Service; b) Platform as a Service; c) Infrastructure as a Service. Deployment models encompass private cloud, community cloud, public cloud and hybrid cloud.

Such technologies as grid-computing, virtualization, service-oriented architectures (SOA) can be viewed as predecessors of cloud computing. In particular, cloud computing extends SOA-applications.

Production resources and capacities can be intelligently sensed and connected into the cloud. The scalability of resources makes cloud computing interesting for business owners, as it allows enterprises to start small projects and invest in more resources only if there are rises in further service demand.

Today most production-related companies require intensive data and knowledge sharing across sites and partnerships. At the same time, the performance of cloud technologies will improve, achieving reaction times of just several milliseconds. As a result, machine data and functionality will increasingly be deployed to the cloud, enabling more data-driven services for production systems.

D. Big Data and Their Analytics

The term *«Big Data»* stands for large data sets that may be analyzed computationally to reveal useful patterns, trends and associations. Ordinarily 3V Big Data model is used. Here we take a 5V concept of Big Data (Figure 6) that associates it with data *volume, variety, velocity, veracity, value*.

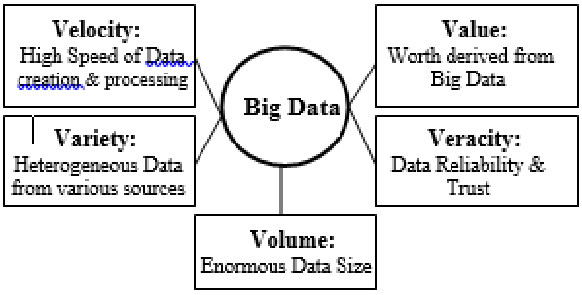

Figure 6. 5V Representation of Big Data

Here an immense data volume means such measurement units as Petabytes: 1 Petabyte = 10^{15} bytes, and higher. Data variety is related to different distributed data sources, data velocity means the speed of data generation and processing, data veracity is attributed to a specific data source and data value expresses its utility. Moreover, the concept of Big Data Value Chain has been introduced in [34]; it encompasses big data capture, processing, interpretation (visualization), while preparing decision.

Now the main challenge in the field of Big Data is that the speed of data generation can exceed the processing capacity. In the near future, this situation can seriously deteriorate. Indeed, IoT will be a major source of big data, contributing massive amounts of streamed information from billions of ICOs. Here M2M communications will generate enormous Internet traffic.

In Industry 4.0 context, the collection and comprehensive evaluation of data from many different sources – production equipment and systems, as well as product lifecycle and enterprise management– becomes a necessary step to support real-time decision making.

So decentralized Big Data Analytics and Information Mining are needed to cope with 5V. Specifically, Visual Analytics supports analytical reasoning by interactive user-friendly visual interfaces. In manufacturing, Data Analytics tools allow to optimize production quality, save energy and improve equipment.

Although many useful approaches and technologies to cope with Big Data, such as MapReduce, Hadoop, Disco, have been successfully implemented, the need in new paradigms in Data Science becomes crucial. Mining Information and Discovering Knowledge from Big Data requires the support of special techniques and new advanced technologies, in particular, data granulation and intelligent clustering methods and tools [35, 36].

E. Cybersecurity

With the increased connectivity and use of standard communications protocols that come with Industry 4.0, the need in *cybersecuirity* to protect critical industrial systems and manufacturing lines from malware and cyberattacks danger becomes crucial. Here the term *malware* encompasses all types of cyberdangers, including viruses, troyans, various spy programs, etc.

A well-known example of successful cyberattack was the use of Stuxnet virus against Iranian nuclear objects: it deteriorated the operation of about 1000 centrifuges for uran concentration. This virus had unique characteristics: for the first time in the history of cyberattacks, virtual object destroyed physical infrastructure.

In case of Internet of Things, the design, deployment and maintenance of communications between heterogeneous and geographically distributed things create grand challenges related to security and privacy. To deal with such hard problems, reliable and safe communications, sophisticated identity and secure access management of machines and users are essential.

Today CPhS and IoT devices seem to remain vulnerable with respect to cyberattacks. Thus, the development of International Standards in the field of Cybersecurity remains a keynote task. These new standards can be based on USA Federal Standard of Cyberrisks Management, NIST Special Publication 800-39, the Common

Vulnerability Scoring System, CVSS, the ISO/IEC31010 Standard supporting risk multi-criteria analysis, etc.

F. Intelligent Simulation and Augmented Reality

The advent of the Industry 4.0 initiative has brought serious changes to the *simulation paradigm* [37]. Now it supposes modeling of manufacturing and other systems by using virtual factory and digital twin concepts. The idea of digital twin extends the use of simulation techniques to all phases of the product lifecycle, where the products are developed and thoroughly tested in a virtual environment. Combining the real life data with the simulation results enables the rise of productivity and the improvement of product quality. Thus, simulations will be used more extensively in plant operations to leverage real-time data and mirror the physical world into a virtual model, which can include machines, products, and humans.

The new simulation paradigm is closely related to considerable technological advances of augmented reality. The last one brings users the chance to experience an augmented world by overlaying virtual information in the real world. This way the user can be in touch with both the real and virtual manufacturing worlds and receive real-time data or statistics.

For Industry 4.0, this may bring several advantages. It can be the perfect method to represent relevant information for technicians and workers in the enterprise, allowing them to watch real time information from the work they are performing. This is a suitable way to improve decision-making procedures and working operations.

Augmented-reality-based systems support a variety of services, such as selecting parts in a warehouse and sending repair instructions over mobile devices. Another great advantage is the possibility of enhancing industrial training and learning while reducing risks and costs.

In our opinion, an adequate extension of RAO intelligent simulation environment (see [38]) can provide a good solution for enabling intelligent simulation in an augmented reality.

G. Additive Manufacturing

Additive manufacturing is a transformative approach to industrial production that enables the development of lighter, stronger parts and systems [1,25]. To differ from usual manufacturing, additive manufacturing (AdM) adds material to create an object. The processes of 3D printing and rapid prototyping are actually viewed as AdM components. Methods and tools of AdM are widely used in Industry 4.0 to produce small batches of customized products. High-performance, decentralized AdM systems reduce transport distances and stock on hand.

In perspective, a special attention will be paid to combined approach based on «additive-subtractive» manufacturing [39].

H. Collaborative Robots

In the framework of Industry 4.0 *robots* become more autonomous, intelligent and cooperative. Here the concepts of collective and collaborative robotics are of special concern. *Collective robotics* considers various groups of robots working collectively to solve a problem. It investigates both teams of cognitive robots and swarms of reactive robots [40,41]. In its turn, *Collaborative Robotics* (briefly, *Cobotics*)[42] deals with *cobotic systems*. A cobotic system is a «man – robot» system, where the participants collaborate in synergy to perform some tasks.

Collaborative robot is intended to physically interact with humans in a shared workspace. This is the difference with respect to conventional industrial robots, that operate autonomously or with a limited guidance.

In order to perform such a joint work hand by hand with human beings, any cobot needs to be equipped with powerful onboard computer and complex sensor system, including an advanced computer vision and learning facilities. It allows prevent the collisions of robot with human partners and obstacles, as well as operate in case of software crash.

To differ from classical master-slave relations, human-robot partnership in cobotic systems is based on collaboration via interactive information management, where the robot partner can initiate the dialogue with human partner to precise the task, request additional data or obtain his evaluation of learning results. New opportunities for cobotic applications in Industry 4.0 are opened by a strategy of direct teaching «do as I do» by showing the necessary motions to the robot.

Therefore, the main requirements for cobots are focused on safety, light weight, flexibility, versatility, and collaborative capacity.

Without the need of robot's isolation, its integration into human workspace makes the cobotic system more economical and productive, and opens up many new opportunities to compare with classical industrial robots. On the one hand, cobots increase information transparency via their ability to collect data and pass it on to other systems for analysis, modeling and so on. On the other hand, they provide technical assistance, in the sense that they "physically support humans by conducting a range of tasks that are difficult, too exhausting, or unsafe for their human co-workers" [43].

According to ISO 10218, the following classes of industrial cobots can be viewed: a) robots-manipulators sharing a workspace with humans (for instance, on the assembly line) to facilitate their workload (as a first interactive industrial robot Baxter); b) mobile transportation robots, as well as mobile robots working in production rooms together with people; c) industrial multi-robot systems. All these robots need the status of artificial cognitive and understanding agents.

IV. HOW TO BUILD ARTIFICIAL «UNDERSTANDING» AGENTS?

The development of Industry 4.0 supposes a total enterprise agentification, where people, robots, industrial equipment (machines and materials), manufacturing software tools and even enterprise products form an Intelligent Organization as a System of Multi-Agent Systems (MAS).

Most of these MAS must include cognitive, collaborative, «understanding» agents.

Let us recall some basic features of human cognition, which are of special interest for developers of artificial cognitive agents (also see [44,45]). Firstly, cognition is an open system based on both available knowledge and current data perception. Secondly, cognition does not make straight conclusions, but generates hypotheses, and these hypotheses should be confirmed or denied. Thirdly, agent cognition is intrinsically linked with the organization of action (as information process, physical movement or local environment change). And fourthly, cognition is tightly connected with understanding. On the one hand, the cognitive capability itself and the result of action strongly depend on the reached understanding level (pre-understanding). On the other hand, human understanding is specified by cognitive capacities, available knowledge and language structure. Although, natural language understanding is driven not so much by purely linguistic factors as by extra-linguistic factors, including personal experience and presupposition.

Understanding is a necessary condition for efficient communication between cognitive agents and their joint work. It is obvious that the human-robot cooperation [42], development of Social Internet of Things [46] and Social Cyberphysical Systems [47,48] require some mutual understanding.

Understanding is not a new problem for AI, but earlier it was mainly considered in the context of natural language processing and text analysis. Such understanding objects, as behavior, decisions, situations, remain almost unexplored.

Let us take the following basic definition from [44]: *Understanding* is a *universal cognitive process* (operation) that evaluates an analyzed object (text, behavior, situation, phenomenon) on the basis of some standard, norm, pattern.

This definition has an axiological nature. It is founded on value theory, because any evaluation implies some value (or logical inference from accepted values by using some general rules) [49]. Two basic operations to enable understanding are: a) the search for some norm and its formal representation; b) justification of the norm's applicability in a specific situation.

The level of agent task understanding can be specified by evaluating the results of his actions, which should not contradict the norms of agent behavior.

Norms are social bans and constraints imposed on an agent by an organization (community). They represent a special case of evaluations: these are socially tested and fixed assessments.

The formal model of norm viewed as a prescription to action is given by a quadruple:

$$NORM = \langle A, act, W, M \rangle.$$

where A is a set of agents to whom a norm is addressed, $act \in ACT$ is an action being an object of normative regulation (the norm content), W is a set of worlds, where the norm is useful (application conditions or specific circumstances in which the action should be performed or not), M is a set of basic modal systems related to the action *act*, for example the system of deontic modalities $M_D = \{O, P, F\}$. Here O stands for "obligatory", P means "permitted" and F is "forbidden".

An evaluation is transformed into a norm by some threat of punishment, i.e. standardization of norms is made through sanctions. Here a typical sanction reasoning pattern is: q («obligatory q») and «if not q, then punishment or degradation». lpar So an information structure of cognitive agent combines both descriptive and normative models (Figure 7).

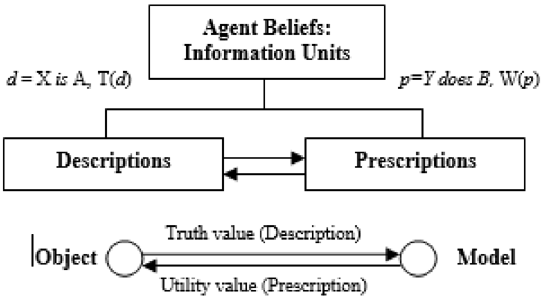

Figure 7. Two Sides of Agent Beliefs

Descriptions d contain the data on the states of environment perceived by the agent, and prescriptions p give the normative information about possible (permitted) actions or behavior patterns. Here a description is characterized by a truth value (description) T(d) and a prescription has a worth (or utility) value W(p). Hence, a truth value is the correspondence between the object and its descriptive model (the object is primary), whereas an utility (worth) value gives the inverse mapping from normative model to this object (the norm is primary). A general agent understanding mechanism also has a dualistic «Description-Evaluation» nature. Every object having a standard prototype (pattern) is understandable, and the reason of misunderstanding consists in the lack of such pattern or its non-obviousness.

It is worth noticing that a pattern as a basis for understanding significantly differs from an example. The example refers to a real existing object, whereas the pattern shows what should be done ideally. The examples are taken to support descriptive models, but references to the patterns and standards serve as justifications of norms and prescriptions.

This dualism is used in «Explanation-Understanding» relationships (Figure 8). Explanation, considered as the reduction of studied phenomenon to the scientific law, representative example or general truth, is based on a descriptive model and helps to understand it, but understanding as searching for rule or standard has a normative basis.

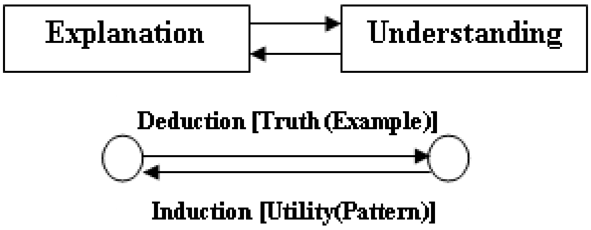

Figure 8. Relationships Between Explanation and Understanding

Logical lattices and bilattices of strong and weak norms and anti-norms have been constructed to provide an artificial agent of Industry 4.0 enterprise with some basic understanding mechanisms.

Furthermore, in modeling artificial societies of Industry 4.0 it is worth employing earlier Russian theoretical studies related to Technetics and Technocenosis theory [50,51]. The term «Technetics» stands for the theory of technosphere evolution. A holistic approach to techniques, technologies, materials, products, waste is taken. An important part of technetics is technogenetics that encompasses the problems of creation and transfer of hereditary information by design and technological documentation and other means.

V. CONCLUSION

To design user-oriented intelligent systems for Industry 4.0, in particular, agent-based, multi-agent systems and artificial societies, we have to integrate usual semantic technologies with open pragmatic technologies, for instance, Peirce's logical pragmatics and modern pragmatic logics (see [45,49]). We need new theoretical methods and models in representing agent's pragmatics (pragmatic worlds and spaces, ontological pragmatics), modeling such pragmatic concepts as beliefs, evaluations and norms, synthesizing pragmatics-based logical and logical-semiotic systems. Here the principle «First pragmatics, then calculus» has to be satisfied. The synergy of semantic and pragmatic technologies is a necessary condition for building advanced intelligent agents.

In our opinion, there exist at least three different ways in developing new generation technologies for Industry 4.0. The first one consists in building intelligent counterparts of main Industry 4.0 components by employing conventional AI technologies, such as: Intelligent Simulation [38], Intelligent Cyberphysical Systems, Intelligent Cloud Computing and so on. The second way supposes «putting the old wine in new bottles», for example, the return back to technocenosis and populations of artificial agents. Finally we have to develop some new trends in AI and Cognitive Sciences, such as General Understanding Theory, Granular Measurements by Cognitive Sensor Networks, Context Aware Search, and so on. The era of artificial-agent-based Industry 4.0 just begins.

VI. ACKNOWLEDGEMENT

The research work is supported by the State Order (Goszadaniye) No 2.7918.2017 and Russian Foundation for Basic Research, Project No 19-07-01208.

REFERENCES

[1] H.Kagermann, J.Helbig, A.Hellinger, W.Wahlster, Recommendations for Implementing the Strategic Initiative Industrie 4.0: Securing the Future of German Manufacturing Industry. *Final Report of the Industrie 4.0 Working Group.*

[2] K.Schwab, The Fourth Industrial Revolution. Geneva, World Economic Forum, 2016, 172 p.

[3] Industry 4.0: Building the Digital Enterprise. Available at: https://www.pwc.com/gx/en/industries/industries-4.0/landing-page/industry-4.0-building-your-digital-enterprise-april-2016.pdf

[4] K.D. Thoben, S. Wiesner, T. Wuest, Industrie 4.0 and Smart Manufacturing – A Review of Research Issues and Application Examples. *International Journal of Automation and Technology*, vol.11, No 1, 2017, pp. 4-16.

[5] M.Skilton M., F.Howsepian, The Fourth Industrial Revolution: Responding to the Impact of Artificial Intelligence on Business. London, Palgrave Macmillan, 2018

[6] V.V.Golenkov, N.A.Guliakina, The Project of Open Semantic Technology for Component Design of Intelligent Systems. Part 1. Principles of Designing. *Ontology of Designing*, 2014, No1, pp.42-64 (in Russian).

[7] V.V.Golenkov, N.A.Guliakina, I.Davydenko, Methods and Tools for Interoperability of Computer Systems. *Open Semantic Technologies for Intelligent Systems*, Minsk, BSUIR, 2019, Iss. 3 (in Russian).

[8] Ch.Peirce, Collected Papers, vol.1-6.Cambridge MA:Harvard University Press, 1965-1967.

[9] V.V.Martynov, Fundamentals of Semantic Coding. Essay of Knowledge Representation and Transformation. Minsk, European Humanitarian University, 2001 (in Russian).

[10] V.B.Tarassov, From Semantic Code to Cognitive Linguistics, Semiotics and Informatics: On Martynov's Scientific Heritage. *Proceedings of the IVth International Conference "Open Semantic Technologies for Intelligent Systems"* , Minsk, BSUIR, 2014, pp.39-48 (in Russian).

[11] M.C.Roco, W.S.Bainbridge (Eds.) Converging Technologies for Improving Human Performance. *NSF/DOC-sponsored report*, Heidelberg, Springer-Verlag, 2003.

[12] Ch. Roser, Industrial Revolutions and Future View. Available at: http://www.allaboutlean.com

[13] V.F.Gornev, Problems and Technologies of Complex Automation. *Computer Aided Design*, part1, No 4, pp.41-44; part 2, No 1, 1999, pp.28-35 (in Russian).

[14] F.Kimura, H.Suzuki, Product Life Cycle Modeling for Inverse Manufacturing. *Proceedings of IFIP WG 5.3 International Conference on Life Cycle Modeling for Innovative Products and Processes* (PROLAMAT' 95, November 29-December 1, 1995), F.L. Krause, H. Hansen (Eds.), Berlin, Springer Verlag, 1996, pp.81-89.

[15] F.B. Vernadat, Enterprise Modeling and Integration: Principles and Applications. London, Chapman and Hall, 1996.

[16] V.B. Tarassov, The Concept of Meta-CIM: from CIM to Enterprise Internet/Intranet-Networks, *Software and Systems*, 1998, No3, pp.19-22 (in Russian).

[17] S.L. Goldman, R.N. Nagel, K. Preiss, Agile Competitors and Virtual Organizations: Strategies for Enriching the Customer. New York, Van Nostrand Reinhold, 1995.

[18] M.Hardwick, D.Spooner, T.Rando, K.Morris, Sharing Manufacturing Information in Virtual Enterprises. *Communications of the ACM*,1996, vol.39, No 2, pp.46-54.

[19] V.V.Emelyanov, V.M.Kureichik, V.V.Kureichik, Theory and Practice of Evolutionary Modeling. Moscow, PhysMathLit, 2003 (in Russian).

[20] V.F. Gornev, V.B. Tarassov, On Some Projects and Initiatives of the International Program on IMS. *Computer Aided Design*, 1999, No 2, pp.42-46 (in Russian).

[21] R.H.Brown,H.Syntera, Global Manufacturing in the 21st Centrury”. Final Report. IMS, 1999.

[22] TOVE Ontology Project 2010. Available at: http://www.eil.utoronto.ca/enterprise-modelling.

[23] C.Baur, D.Wee, Manufacturing’s Next Act. McKinsey & Company, June 2015.

[24] S.C. Suh, U.J. Tanik, J.N. Carbone, A.E. Eroglu (Eds.), Applied Cyber-Physical Systems. Heidelberg, Springer-Verlag, 2014.

[25] Ph. Gerbert, M. Lorenz, M. Rusmann, et al. Industry 4.0: The Future of Productivity and Growth in Manufacturing Industries. BCG, April 2015.

[26] J.L.G.Dietz et al. Enterprise Engineering Manifesto, *Advances in Enterprise Engineering I, Lecture Notes in Business Information Processing*,2011, Vol.10.

[27] Yu.F. Telnov, Enterprise Engineering Based on Intelligent Technologies. *Information-Measurement and Control Systems*, 2013, No 11, part 2, pp.55-60 (in Russian).

[28] H. Sundmaeker, P. Guillemin, P. Friess, S. Woelffle (Eds.), Vision and Challenges for Realizing the Internet of Things. Luxembourg, EU, CERP IoT, 2010.

[29] K.Ashton, That Internet of Things, *RFID Journal*, 22 June 2009.

[30] Gartner, Internet of Things. Available at: http://www.gartner.com/it-glossary/internet-of-things/

[31] D.Uckelmann, M.Harrison, F.Michahelles, (Eds.) Architecting the Internet of Things. Heidelberg, Springer-Verlag, 2011.

[32] P.Mell, T.Grance, The NIST Definition of Cloud Computing Gaithersburg: National Institute of Standards and Technology, 2011.

[33] N.K.Sehgal, P.Ch.Bhatt, Cloud Computing: Concepts and Practices. Heidelberg, Springer-Verlag, 2018.

[34] H.J.Miller, P.Mork, From Data to Decisions: a Value Chain for Big Data. *IT Prof*,2013, vol.15, pp.57-59.

[35] L.Zadeh, Toward a Theory of Fuzzy Information Granulation and its Centrality in Human Reasoning and Fuzzy Logic. *Fuzzy Sets and Systems*, 1997, vol.90, pp.111-127.

[36] W.Pedrycz, Granular Computing for Data Analytics: a Manifesto of Human-Centric Computing.*Soft Measurements and Computing*, 2018, vol.2, No 7, pp.4-21.

[37] B.Rodic, Industry 4.0 and the New Simulation Modeling Paradigm. *Organizacija*, vol.50, No 3, 2017, pp.193-207.

[38] A.Artiba, V.V.Emelyanov, S.I.Iassinovski, Introduction to Intelligent Simulation. RAO Language. Dordrecht, Kluwer Academic Publishers, 1998.

[39] G.B.Evguenev, Methods of Programming Combined Additive-Subtracting Processing. *Proceedings of Higher Education Institutions: Machine Building*, 2017, No 4, pp.47-56 (in Russian).

[40] S.Kernbach (Ed.) Handbook of Collective Robotics: Fundamentals and Challenges. Singapore, Pan Stanford Publ. Pte. Ltd., 2013.

[41] V.E.Karpov, I.P.Karpova, A.A.Kulinich, Societies of Robots. Moscow, Lenand, 2019 (in Russian).

[42] M.Peshkin., J.Colgate, Cobots. *Industrial Robots*, 1999, vol.26, No5, pp. 335-341.

[43] J.Faneuff, Designing for Collaborative Robotics. Sebastopol Ca, O’Reilly, 2016.

[44] V.B.Tarassov, Problem of Understanding: the Present and Future of Artificial Intelligence. *Proceedings of the 5th International Conference "Open Semantic Technologies for Intelligent Systems’*, Minsk, BSUIR, 2015, pp. 25-42 (in Russian).

[45] V.B.Tarassov, Information Granulation, Cognitive Logic and Natural Pragmatics for Intelligent Agents.*Open Semantic Technologies for Intelligent Systems*, 2018, Issue 2, pp.45-54.

[46] L.Atzori, A.Iera, G.Morabito, M.Nitti, The Social Internet of Things – When Social Networks Meet the Internet of Things: Concept, Architecture and Network Characterization. *Computer Networks*, 2012, vol.56, No 16, pp.3594–3608.

[47] F.Dressler, Cyber Physical Social Systems: Towards Deeply Integrated Hybridized Systems. *Proceedings of 2018 International Conference on Computing, Networking and Communications*, 2018, pp.420-424.

[48] E.M.Frazzon, J.Hartmann, Th.Makuschewitz, B.Scholtz, Towards Socio-Cyber-Physical Systems in Production Networks. *Procedia CIRP*, 2013, vol. 7, pp.49-54.

[49] A.A.Iwin, Logic of Evaluations and Norms: Philosophical, Methodological and Applied Aspects. Moscow, Prospect, 2016 (in Russian).

[50] B.I. Kudrin, Introduction to Technetics. Tomsk, TGU Press, 1993 (in Russian).

[51] D.A.Pospelov, V.I.Varshavsky, The Orchestra Plays without a Conductor. Reflections on Evolution and Control of Some Technical Systems. Moscow, Librokom, 2009 (in Russian).

СЛЕДУЮЩАЯ СТАДИЯ ИНДУСТРИИ 4.0: ОТ КОГНИТИВНЫХ К КОЛЛАБОРАТИВНЫМ И «ПОНИМАЮЩИМ» АГЕНТАМ

Тарасов В. Б.
ФГБОУ ВО «Московский государственный
технический университет им. Н.Э.Баумана»

В работе показана роль искусственных когнитивных, коллаборативных и «понимающих» агентов в развитии технологий Индустрии 4.0. Обоснована целесообразность интеграции открытых семантических и прагматических технологий в русле интеллектуализации Индустрии 4.0. Предварительно изложены основные характеристики и технологии предыдущих промышленных революций. Особое внимание уделено эволюции производственных систем в XX-м веке. Проанализированы темы и основные результаты первой международной программы IMS по интеллектуальным производственным системам. В основной части статьи представлены главные идеи и принципы стратегии Индустрия 4.0. Ее сердцевина – киберфизические системы, которые обеспечивают единство физического и виртуального миров на производстве. Описано семейство базовых технологий и средств Индустрии 4.0, которое включает: технологии инжиниринга и интеграции предприятий; интернет вещей; облачные технологии; большие данные и средства их аналитики; имитационное моделирование; виртуальную и дополненную реальность; аддитивные технологии; автономные и коллаборативные роботы; средства обеспечения кибербезопасности. Выдвинут тезис о проведении сквозной агентификации предприятий Индустрии 4.0, согласно которому они понимаются как смешанные сообщества естественных и искусственных агентов. В заключительной части статьи рассмотрена задача построения искусственных «понимающих» агентов, для решения которой использованы аксиологический подход и прагматические логики.

Received 21.12.18