The challenges in modelling of “Industry 4.0”-compliant manufacturing systems

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Abstract. Modern manufacturing systems that follow the “Industry 4.0” philosophy reject the traditional understanding of the factory as an entity placed in the time and the space. The introduction of the Virtual Enterprises (VE) and Virtual Manufacturing Networks (VMN) has increased the complexity of interconnections between the resources involved in the production process. This fact is also reflected in the complexity of models of such systems, especially if the system should be considered at different levels of generality. What’s more, the components of such system and their roles can change during the time, as the result of system’s self-organizing capability. These changes could have different rate and intensity, and these parameters play important role during the selection of the methodology of modelling. The paper raises the problem of modelling of such systems in several aspects, like variability of the structure or the system’s analysis depth. The considerations will also take into account the methods based on the agents and holons methodologies and their usefulness in modelling from the point of view of the need to quickly change the scale of the model.

1. Introduction

The beginning of the 21st century is a time of significant development of mobile techniques. The development of wireless communication standards has enabled the implementation of modern machine control systems that allowed large-scale information exchange. In turn, this process has led to the development of modern business management methods that focus on the most effective use of information technology. This trend is reflected in the so-called Fourth Industrial Revolution and became the starting point for development of the "Industry 4.0" philosophy.

The term “Industry 4.0” has no strict definition. It is used to indicate the changes that are taking place in the industry right now and which are seen as the next industrial revolution. The designation "4.0" on the one hand refers to the three previous industrial revolutions, while on the other to the numbering that is frequently used to designate the software version – this indicates the strong connection with the field of IT. After the First Industrial Revolution that has introduced the steam engine and mechanization, the Second has used electricity and allowed to run mass production, while the Third one has enabled the use of electronic devices in the control systems. The Fourth Industrial Revolution goes further and introduces the cyber physical systems (CPS). Such devices connects the real world with the virtual reality through the computing and communication infrastructures. In contrast to embedded devices, which are designed as standalone devices, cyber-physical systems are
network-oriented and fit in with the worldwide trend of the availability of information from anywhere in the world.

The use of cyber-physical systems opens new possibilities in approaching to the manufacturing process. First of all, these systems combine two layers: physical and virtual, existing in the computer's memory. The virtual model goes beyond the limits defined by the factory area or the time zone. For this reason, it is possible not only to combine the resources of various companies, but also to use the global market offers and services, without the need for long-term searches and analyzes. It is possible to create Virtual Enterprises and Virtual Manufacturing Networks, use of Cloud Manufacturing or, etc. The last two concepts are considered similar, although as some authors indicate [1,2], the difference lies in the approach to the usage of the network services, which is a matter of course in Cloud Manufacturing, whereas Ubiquitous Manufacturing may not require access to the network. Both approaches can be used complementarily and, as Ferreira et al [3] note, Cloud Manufacturing and Ubiquitous Manufacturing ensure that factories have almost unlimited production capacity and constant availability of manufacturing services.

A variety of solutions in the field of production organization in connection with a multi-level information flow system, significantly hampers the modelling of the manufacturing process. Moreover, at the level of a single machine, there exist systems that do not have a direct impact on the schedule of the production process, but are important components of the machine that may be associated with the need to eliminate adverse phenomena – the example of such system may be the mechatronic device for active vibration damping [4]. Modelling of all dependencies is often unnecessary and even impossible, hence the approach to modelling the production system must be a compromise between the detailedness and the clarity of the description. In the case of a system based on the "Industry 4.0" philosophy, there is another important aspect, because the real system is linked with its virtual counterpart, existing in the form of data stored in the network infrastructure. It should also be noted that each device can change its role in real time in the production process (performance, assortment etc.).

The mentioned features will be the subject of considerations in terms of the usefulness of known modelling methods, in order to obtain the best system mapping. The results will be discussed in the further part of this paper.

2. The overview of selected methods of manufacturing systems modelling

This section will present the overview of selected methods of manufacturing system modelling. The aim is to discuss the old and present methods in order to highlight the most characteristic features of each of them that could be later referred to the modelling of “Industry 4.0”-compliant system.

2.1. Object-oriented approach and UML language

The object-oriented modelling (OOM) is one of the most known approach to creation of models using computer and the engineering software. The idea behind the OOM is to create virtual models of the real objects, where the real world object has its own “twin” in the virtual world represented by the information system object. Any real world object is described by an entity, so attributes of an entity correspond to the properties of an object [5]. The most important features of the OOM could be shortly described as:

- **Inheritance/Multiple inheritance** – the new object can be created as a “child” of the existing object (“parent”) or objects (“parents”); the newly created object inherits the attributes of parent object,
- **Types** – usually all of the objects in the particular system are not completely different and have certain level of similarity; according to these similarities, objects can be grouped, while the common features of such a group can be defined as the type of an object,
- **Methods** – the entities are able to process the information and the methods are descriptions how to do that; it is a part of an entity that determine how it “behaves”,


• **Encapsulation** – this feature is responsible for external visibility of the entity attributes and methods; some of attributes are visible only for internal methods and are called private, while other can be accessible from outside world, by another entity (figure 1),

• **Polymorphism** – in the very simple words, one structure may be used in different classes and adjusted to the needs.

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**Figure 1.** Encapsulation. Boxes represent methods, circles – attributes. Dot-shaped boxes and circles represents private methods and attributes that are not visible from the outside [5].

The object-oriented approach has become very popular in both system modelling and programming. From this point of view, it gives the opportunity to describe very complex systems including the relationship between the components and use the same methodology for modelling the real system and the information flow. The obtained model is simple to understand and can be modified in a simple way, because in most cases it is needed to do required changes only in particular objects, without necessity to analyze the whole model. The object-oriented way of modelling has been also used for creation of FMS models [6,7].

Object-oriented models are often represented using UML (Unified Modeling Language). It is a form of graphical notation of the structure and behaviour of objects in the modelled system. Next to UML, Petri Nets are also used in OOM, which will be discussed in the next section.

2.2. **The use of Petri Nets – graph methods approach**

Petri Nets are the graphical form of representation of dependencies between objects occurring in the system. They describe not the structure but the behaviour of the system. The Petri Net is the form of a graph illustrating transitions between successive states and consists of places, transitions and arcs (figure 2). Arcs are directed from a place to a transition or from a transition to a place, but never connect places or transitions. Places can contain a number of marks, which are called tokens. Tokens can be moved from one place to another when the condition (represented by the transition) is met – in such situation it is said that the transition was fired.

**Figure 2.** The components of Petri Net.
Petri Nets are willingly used in manufacturing systems modelling [8-13]. Among the advantages of such approach, the most important ones should be mentioned:

- Petri Nets are intended for modelling discrete systems and manufacturing systems are the discrete one; events corresponds to transitions, while activities are associated to the firing the transitions [9],
- Due to the place/transition duality Petri Nets are able to depict control policies completely [9],
- At the system design stage, Petri Nets offer graphical representation and precise formalism [9],
- Petri Nets allow the modelling of true parallelism, offer the possibility of progressive modelling and easy integration of timing constrains [9],
- Because of its graphical form, Petri Nets are self-documenting and easy to understand [13],

Petri Nets are still being actively developed. Based on classical methodology, new varieties are created, like Activity-Oriented Petri Nets [13], Dualistic Petri Nets [14] or Coloured Petri Nets [15]. Some of them are backward-compatible extensions, while the others introduce new features.

2.3. Agent-based and holon-based approach

The agent-based and the holon-based approaches to modelling of manufacturing systems are two, quite similar methodologies, although they was derived from different roots. The definition of the holon is fully clear, as it comes directly from the philosophical sciences. Arthur Koestler in [16] has written that “holon is a system of relations which is represented on the next higher level as a unit, that is, a relatum.” Further Koestler states that each holon has an internal set of rules that guides its activity. Once excited with an external signal, the holon will act according to these rules, activating its subunits in a strategic order, guided by feedback and feedfowards from the environment. As it can be seen, the holons are autonomous units that can act independently, without receiving instructions from the environment. In reference to the manufacturing systems, holons “assist the operator in controlling the system: holons autonomously select appropriate parameter settings, find their own strategies and build their own structure.” [17] In this way, the Holonic Manufacturing Systems (HMS) are created. Holons could be organized into forms called holarchies that represents the structure of mutual connections between holons. Holarchy can combine the hierarchical organization with the horizontal one, while the single holon could be a member of more than one holarchy [18]. Structures based on the holon methodology can be represented in the computer memory using software that support the so-called Function Blocks in accordance with IEC 61499 standard. Regarding the manufacturing systems, the holonic approach is frequently used [17,19-21] in modelling.

Concerning the agent-based approach to the modelling of manufacturing systems, it should be stated that there is no explicit definition of agent. The term “agent” for many years has been used in the medical sciences and chemistry, then migrated to the computer sciences. Regarding the software development, the “agent” has started the new programming style. Agent-based models have replaced object-based models and even gone further, establishing the definition of multi-agent systems and of “intelligent agents”. Franklin and Graesser [22] have introduced the following definition: “An autonomous agent is a system situated within and a part of an environment that senses that environment and acts on it, over time, in pursuit of its own agenda and so as to effect what it senses in the future”. This approach has been almost directly transferred to the industrial environment by Unland [23], who defined the agent as “an agile and robust software entity that intelligently represents and manages the functionalities and capabilities of an industrial unit”. Unland also lists some key features of industrial agent, like being autonomous unit, goal-oriented behaviour and efficient communication with the other agents.

Although holons and agents represent different approach to modelling and are formally distinguished, today these differences are blurred. The analysis carried out by Botti and Giret [17] shows that the holon is a special case of an agent. Horling and Lesser [24] list several examples of agents organizational structures and mention about holarchy among them. In turn Unland [23] and Barbat et. al. [25] claim that synergistic, holonic approach together with the agents methodology can
overcome limitations of each of the methods and can give better results in dynamic environments. A reference to combining of both methods can also be found in [26] and [27].

3. Challenges in modelling the “Industry 4.0”-compliant manufacturing systems
The development of computer techniques in production management aims to supervise all phases of the product life cycle, from design to recycling. An indispensable element, supporting such activities is the ability to create models for computer simulation of manufacturing or logistic processes [28]. Due to the high complexity of modern manufacturing processes, the use of Cloud Manufacturing, creation of Virtual Manufacturing Networks, etc., modelling is significantly hindered – on the one hand due to the dispersion and decentralization of resources, on the other due to dynamically changing configuration of the production environment.

Explanation of contemporary challenges regarding modelling of manufacturing systems that are consistent with the "Industry 4.0" philosophy is best carried out using the example. Let's consider the simplified model in which cell phones are manufactured (figure 3a). The main manufacturer relies on the supply of components in the form of CPU and touch screens that come from external contractors. In this case, it should be assumed that success, as an appropriate amount of produced phones per unit of time, depends – among other things – on the continuity of supply of components of appropriate quality. The classic model would include the phone factory, while both component suppliers and potential customers would be represented by input and output storages – more precisely by maintaining the right amount of components in the mentioned storages. However, it should be noted that the "Industry 4.0" philosophy is based on cyber-physical systems, what is mean that such systems not only ensure continuous monitoring of production, but also can predict the future behaviour of the whole manufacturing system and react to possible emergency situations before they happen. Such reaction may involve the need to reorganize the process, e.g. by changing the loads of individual machines. Therefore it can be assumed that fulfilling the "Industry 4.0" requirements, the main producer's manufacturing system will be able to react in advance to changes taking place in the suppliers' factories – e.g. if the supplier detects defects in the produced screens, the phone manufacturer will be able to react in advance and ensure production continuity through making the order from another supplier.

Another example of a complex manufacturing system may be the use of external services related to Virtual Manufacturing Networks in the production process (figure 3b). In accordance to the idea, some of the tasks are carried out on machines that are the equipment of different factories, but are also the part of the chain of the manufacturing process. As before, looking at this model from the point of view of cyber-physical systems, it is not possible to omit the important aspect of linking resources of various enterprises, and thus communication between them.

The problem of modelling large structures is connected with the issue of scalability of the model. Looking at the model from the perspective of the connection of several companies refers to a completely different level of detail than looking at a specific section of the production line. The essence of scalability is the ability to observe closely selected aspects of a given model without the need to filter out unnecessary information.
The aim of this study is to identify the challenges of modelling of manufacturing systems based on the "Industry 4.0" philosophy, but it was not the goal to identify solutions to these problems. Conducting general considerations, based on the content of Section 2, it is possible to indicate some directions of research that will lead to the development of new or improved existing modelling methods, in terms of suitability in modelling of "Industry 4.0" compliant manufacturing systems. Methods based on object-oriented approach (UML language) or on Petri Nets are still being developed [29, 30] and adapted to the new requirements. However, even a cursory analysis of literature, leads to the conclusion that the attention of researchers focuses on agent-based and holon-based approach [31,32]. Using both of these methods provides a synergy effect, allowing achieving intelligent, goal-oriented, self-organizing structures and at the same time allows looking at the production system from the right perspective and the right level of detailedness. The special feature of the holon, which is the possibility of belonging simultaneously to several holarchies and the possibility of changing this affiliation dynamically, allows the modelling of dynamic structures and look at the production process from the perspective of the product being created [33]. There are many environments that support the methodology of agents and holons, such as NetLogo, JADE or FBDK that works on the base of previously mentioned Function Blocks and is compliant with the IEC 61499 standard. It is also worth to mention that the Function Blocks have been successfully used in modeling Human & Industrial Robot (HIR) cooperative workcell, where a human cooperates with a robot (cobot) performing activities within the confines of technological process [34].

4. Conclusions
The Fourth Industrial Revolution ("Industry 4.0") is a concept related to the introduction of cyber-physical systems to the manufacturing process. CPS connect the physical world of the production line with the virtual world of data transferred between computer systems. The availability and processing of large amounts of production-related data enabled the possibility of implementation of artificial intelligence systems that continuously monitor the manufacturing process, optimize it and predict the events that could disrupt the work. The presence of computer systems has also made possible to plan the manufacturing process on the base of resources that are located outside the factory, but are available within the confines of creation of Virtual Enterprises, Virtual Manufacturing Network or as Machine as a Service (MaaS/Cloud Manufacturing). The aim of this paper was, on the one hand, to...
identify challenges in the modelling of manufacturing systems that are the result of implementation of new methods in planning and production, and on the other, to present existing modelling methods and briefly discuss their implementation in the current trend related to the introduction of the “Industry 4.0” philosophy. As part of the discussion, the two examples of manufacturing systems were presented with the reference to the currently used modelling methods. Although the indication a specific modeling method, useful in the description of “Industry 4.0”–compliant manufacturing systems, is not the aim of this study, it should be noted that contemporary research trends are focused on the development of agent-based and holon-based methods.

5. References

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