Available online at www.sciencedirect.com

ScienceDirect

Procedia Computer Science 60 (2015) 1146 – 1155

Procedia Computer Science

19th International Conference on Knowledge Based and Intelligent Information and Engineering Systems

Virtual Engineering Object / Virtual Engineering Process: A specialized form of Cyber Physical System for Industrie 4.0

Syed Imran Shafiq[a]*, Cesar Sanin[a], Edward Szczerbicki[b] & Carlos Toro[c]

[a]*The University of Newcastle, University Drive, Callaghan, 2308, NSW, Australia.*
[b]*Gdansk University of Technology, Gdansk, Poland.*
[c]*Vicomtech-IK4, San Sebastian, Spain.*

Abstract

This paper reviews the theories, parallels and variances between Virtual Engineering Object (VEO) / Virtual Engineering Process (VEP) and Cyber Physical System (CPS). VEO and VEP is an experience based knowledge representation of engineering objects and processes respectively. Cyber–physical systems (CPSs) are the next generation of engineered systems in which computing, communication, and control technologies are tightly integrated. The analysis of basic concepts and implementation method proves that VEO/VEP is a specialized form of CPS and it can play a vital role in the structure building of Industry 4.0. Integration of the two models may result in intelligent machines and advanced analytics.

Peer-review under responsibility of KES International

Keywords: Virtual Engineering Object (VEO), Virtual Engineering Process (VEP), Set Knowledge experience structure (SOEKS), Decisional DNA.

1. Introduction

Efforts are being made around the world to improve the productivity and efficiency in industrial manufacturing which can be achieved by integrating manufacturing with information and communication technology (ICT). The main objective behind this integration is to reap the benefits of the unprecedented advancement in the field of information and communication technologies[1].

The ICT will be utilized to attain an improvement in energy and resource efficiency[2]. Moreover manufacturing applications development will enhance by exploiting ICT features like: robustness, resilience, information security and real time capabilities.

* Corresponding author. Tel.: +61 405408834.
E-mail address: SyedImran.Shafiq@uon.edu.au.

Peer-review under responsibility of KES International
doi:10.1016/j.procs.2015.08.166

All these ideas lead to the emergence of the new concept of Industrie 4.0[3]. It is a powerful concept which promotes the computerization of traditional manufacturing plants and their eco-systems towards a connected and 24/7 available resources handling scheme. The goal is the intelligent factory, which is characterized by adaptability, resource efficiency and ergonomics as well as the integration of customers and business partners in business and value processes. Industrie 4.0 promotes vision of smart factories and is based on the technological concepts of Cyber Physical Systems (CPS) and Internet of Things (IoT)[3].

CPSs refer to the next generation of engineered systems that require tight integration of computing, communication, and control technologies to achieve stability, performance, reliability, robustness, and efficiency in dealing with physical systems of many application domains[4].

Knowledge engineering plays an important role in cyber-physical systems as there is a need for a unified framework to represent the myriad types of data and application contexts in different physical domains, and interpret them under the appropriate contexts[5]. The concept of Virtual engineering object (VEO) and Virtual engineering process (VEP) is experienced based knowledge representation of engineering objects and processes respectively. This review article investigates whether concept of VEO / VEP can be treated as specific form of CPS and consequently can be utilized in design of Industrie 4.0.

The structure of this paper is as follows: section 2 deals with the basic concepts, objectives and advantages of Industry 4.0, CPS, IoT and challenges faced in implementation. Section 3 describes the concepts of VEO and VEP. Comparison between CPS and VEO is discussed in section 4 and in the last section conclusions of this review are presented.

2. Industrie 4.0 : New industrial revolution

The world was witnessed three major industrial revolutions and the forth one is already on its way as shown in figure 1.The first one had mechanization which lead to improved efficiency , the second one saw the advent of electricity and mass production, the third one was marked by the use of electronics and information technology. In the emerging forth revolution, which is Industrie 4.0 physical objects will form a virtual information network[1, 6].

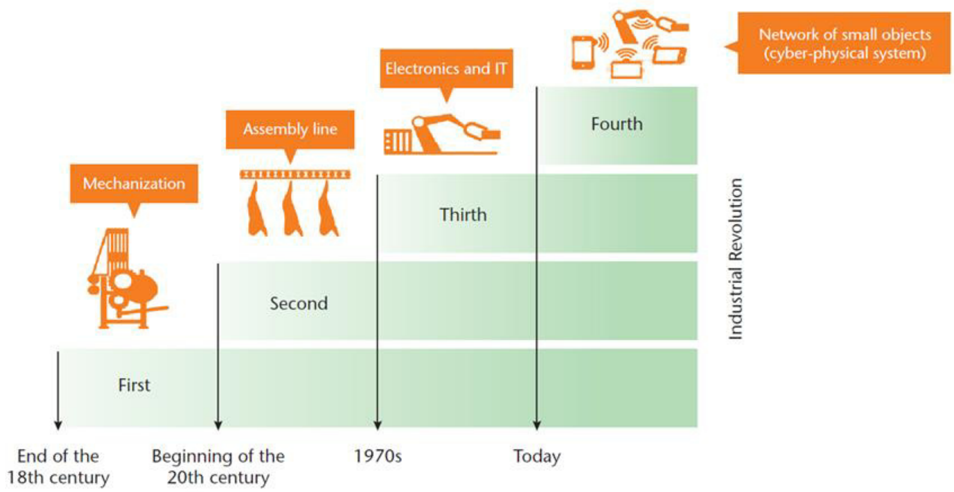

Fig. 1. Emergence of Industrie 4.0[1]

Despite of overwhelming enthusiasm and research going on for Industrie 4.0 worldwide, yet there is no standard/formal definition for it. Some of the definitions found in literature are as follows:

Definition 1: " Industrie 4.0 is the integration of complex physical machinery and devices with networked sensors and software, used to predict, control and plan for better business and societal outcomes"[7].

Definition 2: “Industrie 4.0 is a new level of value chain organization and management across the lifecycle of products”[6].

Definition 3: Industrie 4.0 is a collective term for technologies and concepts of value chain organization. Within the modular structured Smart Factories of Industrie 4.0, CPS monitor physical processes, create a virtual copy of the physical world and make decentralized decisions. Over the IoT, CPS communicate and cooperate with each other and humans in real time. Via Internet of Services (IoS), both internal and cross organizational services are offered and utilized by participants of the value chain[3].

Therefore from the above definitions it is evident that the Industrie 4.0 is combining of intelligent machines, systems production and processes to form a sophisticated network. Moreover it emphasizes the idea of consistent digitization and linking of all productive units in an economy and creating real world virtualization into a huge information system. Industrie 4.0 has to be integration and assimilation from smaller concepts (see figure 2) such as the “Cyber physical systems (CPS)”,"Internet of things (IoT)", “Internet of services (IoS)”, “smart products” etc[6].

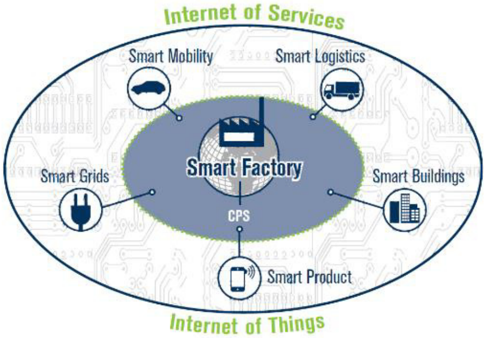

Fig. 2. Framework for Industrie 4.0 and CPS[6]

Objectives of Industrie 4.0

Literature review[1] reveals Industrie 4.0 addresses following key aspects:

- IT-enabled mass customization of manufactured products, in which production must adapt to short batches or even individual needs;
- automatic and flexible adaptation of the production chain to changing requirements;
- tracking and self-awareness of parts and products and their communication with machines and other products;
- improved human-machine interaction (HMI) paradigms, including coexistence with robots or radically new ways to interact and operate in factories;
- production optimization due to IoT-enabled communication in smart factories; and
- radically new types of services and business models contributing to changing ways of interaction in the value chain.

Design and Implementation Strategy for Industrie 4.0

Based on the findings from the literature review[3, 6, 8], in total, six design principles can be derived from the Industrie 4.0 components:

- Interoperability: the ability of physical components, humans and Smart Factories to connect and communicate with each
- Virtualization: virtual copy of physical objects
- Decentralization: the ability of components to make decisions on their own
- Real-Time Capability: the capability to gather and analyse data in real time
- Service Orientation: The services of companies, CPS, and humans are available over the IoS and can be utilized by other participants.
- Modularity: flexible adaptation of Smart Factories to changing requirements by replacing or expanding individual modules

For achieving these design principles, Industrie 4.0 is to be implemented in a dual strategy[1, 6, 9]: Existing basic technologies and experience are to be adapted to meet the special requirements of manufacturing technology, and research and development work is to be conducted into solutions for new production locations and new markets. In that context, attention is to focus on three characteristics:

- Horizontal integration: Horizontal integration refers to the use of these technologies to exchange and manage information across different agents around a manufacturing process such as a resources management system, logistics, marketing, and intercompany value chain.
- Vertical integration: It refers to the integration of various IT systems at different hierarchical levels during a manufacturing process, creating flexible and reconfigurable system.
- End-to-end integration: End-to-end digital integration refers to a holistic digital engineering view, and the goal is to close the gap between product design and manufacturing and the customer.

Potential benefits

Although complexity of Industrie 4.0 system increases but its benefits[1,6] are huge, some of them are:

- More flexibility: Production procedures are more structured and dynamic; are to react more flexibly to changes in demand or breakdowns in the value chain that occur at short notice
- Reduce lead times: Seamless data collection enables the rapid use of production-relevant data for near-term decision-making regardless of the location.
- Customization with small batch sizes: Industrie 4.0 allows the incorporation of individual customer-specific criteria concerning design, configuration, ordering, planning, production and operation as well as enabling modifications to be made at short notice.
- Reduce costs: Companies that optimise their value chains and increase their manufacturing automation thereby reduce their tied-up *capital cost*. Companies can cut their *energy costs* via smart control of their plant facilities. Companies with highly automated production processes tend to require a declining number of low-skilled employees and thus reduce *personal cost*.

2.1. Cyber Physical Systems (CPS)

As discussed in previous section and shown in figure 2, CPS is one major technological concept on which Industrie 4.0 is based on. CPS refers to the convergence of the physical and digital worlds by establishing global networks for business that incorporate their machinery, warehousing systems and production facilities. In the manufacturing environment, these CPSs referred as Cyber Physical Production System (CPPS) comprise smart machines, storage systems and production facilities capable of autonomously exchanging information, triggering actions and controlling each other independently. This facilitates fundamental improvements to the industrial processes involved in manufacturing, engineering, material usage and supply chain and life cycle management[10, 11].

Machines, plants, and factories will be available as data objects, increasingly be connected to a network. Therefore, they become searchable, explorable, and analyzable in the network. This will lead to an explosion of available objects and data, accessible from anywhere[12].

Table 1. CPS requirements and their corresponding advantages

CPS requirements	Advantages
physical objects	intelligent machines
data models of the physical objects in a network	advanced analytics
services based on the available data	people at work

To achieve this vision, it is necessary to capture, analyze, and interact with both the real (physical) and the virtual (digital/cyber) production worlds, with a high level of precision in all dimensions (spatial and temporal)[1,13].

Advanced manufacturing entails the rapid transfer of new knowledge into industrial processes and products. ICT is a key enabling technology to accelerate and improve productivity in manufacturing. Components, products, and other entities in industrial production would get their own identities in the network. They could negotiate with each other or could be interconnected and simulated. Systems could be virtually integrated, tested, and optimized. The digital factory and the virtual commissioning would be accessible to everybody. Algorithms for autonomy optimization can be achieved as shown in table1[1, 12, 14].

Cyber Physical Production System (CPPS)

In industrial manufacturing domain, CPPS is a specialized form of CPS and also shares the same conceptual model. CPS is at level of sensors/actuators and has a more localized knowledge when compared to CPPS which has more contexts at process level as it is an aggregator of CPS's. Both Play different roles, one is at the level of the objects/machines and the other is at the level of the manufacturing line acting in the manufacturing cells. Some formal definitions used for CPPS are:

Definition 1: Application of cyber -physical systems in the manufacturing industry and hence the ability for continuous viewing of product, production equipment and production system under consideration changing and changed processes[28].

Definition 2: Systems that synergize conventional production technology and IT, allowing machines and products to communicate with each other in the Internet of Things[29].

2.2 Internet of Things (IoT) and Internet of Services (IoS)

The Internet of Things and Services is a core technology that is being revolutionized by the emergence of intelligence (intelligent devices, networks, and decision technologies) and complemented by cloud-based systems, cost-effective Internet solutions, secure and robust networks, mobile Internet possibilities, and so forth[2, 3, 6].

2.3 Challenges of implementing Industrie 4.0 and CPS

Apart of general computing and communication challenges like embedment, predictability, flexibility and robustness to unexpected conditions. There are considerable challenges, particularly because the physical components of such systems introduce safety and reliability requirements qualitatively different from those in general purpose computing. Moreover, physical components are qualitatively different from object-oriented software components in their behaviour and abstraction levels[4].

In a broad CPS environment, a large number of models, systems and concepts from an extremely wide range of domains play an important part in shaping that structure. We propose to add VEO/VEP to this vision that will facilitate and open new solutions and services.

3. VEO/VEP: Fusion of the physical and virtual world

In this section, concept and architecture of VEO and VEP is discussed first and then parallels are drawn with CPS.

3.1 Virtual engineering object (VEO)

A VEO is knowledge representation of an engineering artefact, it has three features [23-25]:

(i) the embedding of the decisional model expressed by the set of experience, (ii) a geometric representation, and (iii) the necessary means to relate such virtualization with the physical object being represented.

A VEO is a living representation of an object capable of capturing, adding, storing, improving, sharing and reusing knowledge through experience, in a way similar to an expert in that object. A VEO can encapsulate knowledge and experience of every important feature related with an engineering object. This can be achieved by gathering information from six different aspects (chromosomes) of an object viz. Characteristics, Functionality, Requirements, Connections, Present State and Experience as illustrated in Fig. 3.

VEO of an engineering object implies that all the knowledge and experience related with that object is stored in a structured manner in a repository. This information not only can be used for decision making regarding its better operational performance but also can be utilized in areas like maintainability, serviceability and reliability of the object. The concept VEO involves the interlinking of the body of knowledge of connected objects, with the aim of constructing subclasses consistent enough for the purposes of the classification scheme[15].

VEO is developed on the concept of cradle-to-grave approach, which means that the contextual information and decision making regarding an engineering object right for its inception until its useful life is stored or linked in it. The knowledge representation technique of Set of experience knowledge structure (SOEKS)-Decisional DNA (DDNA) is used for developing VEO as it provides dynamicity to overcome issues of representing complex and discrete objects.

SOEK-DDNA[16-19] is proposed as a unique and single structure for capturing, storing, improving and reusing decisional experience. Its name is a metaphor related to human DNA, and the way it transmits genetic information among individuals through time. Based on the literature review[18, 22, 26] it is evident that SOEKS-DDNA is a novel technique to reuse the experience and the formal decisions made in day-to-day activities. It can be implemented on various platforms (e.g., ontology, reflexive ontology, software based, fuzzy logic, etc.) in multi-domains, which makes it a general and universal approach.

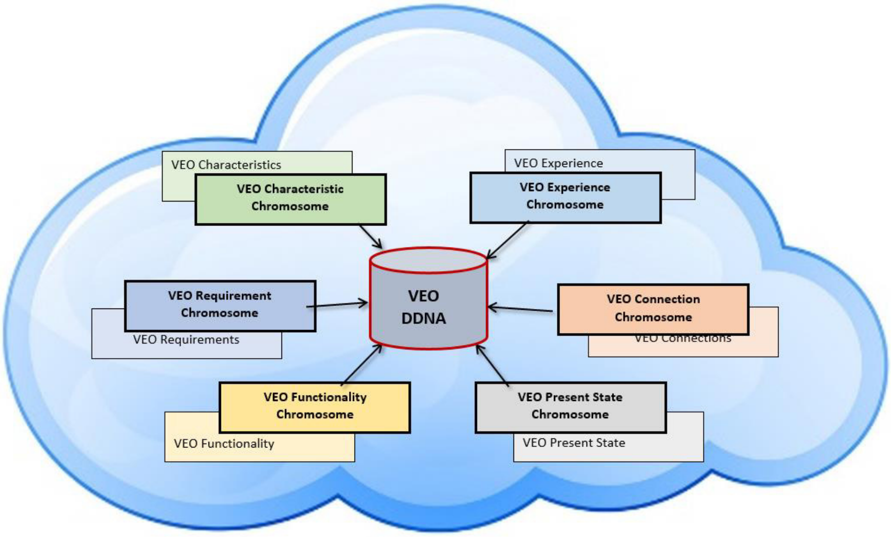

Fig. 3. VEO Structure[21, 22]

The changing machining conditions such as spindle thermal deformation, tool failure, chatter, and work piece deformation induced by clamping force, cutting force, and material inner stress have significant impacts on machining quality and efficiency. Figure 4 exhibit that VEO will cater decision making regarding problems which may emerge during the machining process due to complex conditions at the machining level.

3.2 Virtual engineering process (VEP)

In manufacturing environment collection of components/tools/objects constitute a process and combination of process constitutes a system as depicted in fig. 4. Following this pattern virtual representation of artefacts in the form of VEO has already been achieved as discussed in section 3.1.

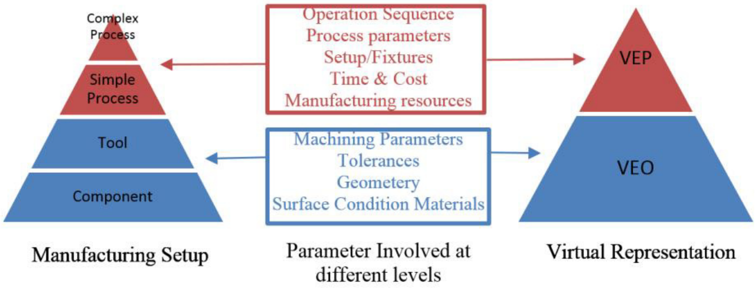

Fig. 4. Correlation between physical and virtual world

Virtual engineering process (VEP) is a knowledge representation of manufacturing process/process planning of artefact having all shop floor level information regarding operations required; their sequence and resources needed to manufacture it as shown in fig 4. VEP deals with the selection of necessary manufacturing operations and determination of their sequences, as well as the selection of manufacturing resources to "transform" a design model into a physical component economically and competitively.

Process planning is combination of information regarding the operation required, manufacturing sequence, and machines required[20]. In addition to this, for VEP, information of all the VEO's of the resource associated with the process is also required. Therefore to encapsulate knowledge of the above mentioned areas the VEP is designed (figure 5) having following three main elements or modules:

(i) **Operations:** In this module of VEP all the information related with the *operations* that are required to manufacture an engineering object is stored. This includes knowledge in the form of SOEKS related to operation process and scheduling. Furthermore functional dependencies between operations are also part of *operations*. These are sub categorized and there interaction planning functions are given below:
- Scheduling route- based on global and local geometry.
- Processes- process capabilities, process cost.
- Process parameters- tolerance, surface finish, size, material type, quantity, urgency

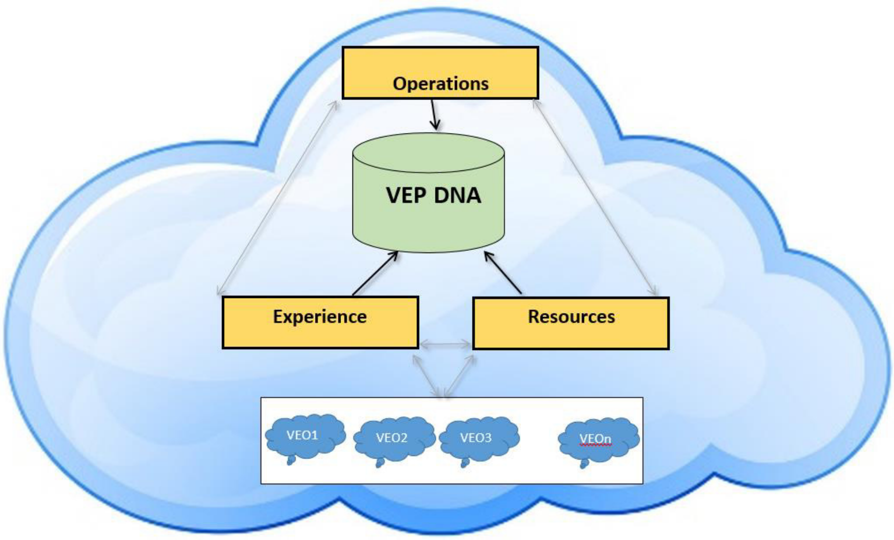

Fig 5. VEP architecture

(ii) **Resources**: Information based on the past experience about *resources* used to manufacture a component mentioned in *operations* module of VEP is stored here. The knowledge of the machine level stored in this section is as follows:

- Machine and tool selections –machine availability, cost machine capability, size , length, cut length, shank length,, holder, materials , geometry, roughing and finishing
- Fixture selection -fixture element function, locating, supporting, clamping surfaces, stability

Furthermore as discussed in section 3.1 the information of VEO categorized under *characteristics*, *requirements*, *functionality*, *present state*, *connections* and e*xperience* is also linked in this section.

(iii) **Experience**: In the *experience* module, links to the SOEKS of VEO's along with VEP having past formal decisions to manufacture engineering components are stored. They represent the links to SOE's based on past *experience* on that particular machine to perform given operation along with operational and routing parameter.

Salient Features of VEO/VEP

As discussed in previous section, VEO/VEP works on the knowledge representation technique of SOEKS and Decisional DNA. Experimental case studies[21, 27] has proven that DDNA based VEO/VEP knowledge system will have following features:

- Versatility and dynamicity of the knowledge structure, which provides flexibility to change according to the situation.
- Storage of day-to-day explicit experience in a single structure, which makes it ever evolving.
- Transportability, adaptability, and shareability of the knowledge.
- Predicting and decision-making capabilities based on the collected past experience.
- Achieving decisional; having the right quality and quantity of knowledge at the right time.

4. VEO/VEP : A tool for building CPS and Industrie 4.0

Analysis of Industrie 4.0, CPS and VEO/VEP reveals that there are fundamental similarities amongst these concepts both at philosophical as well as practical level. In industrial manufacturing domain, CPPS are another specification of CPS at the level of process. CPPS is collection of CPS's in a similar fashion as VEP is of VEO's. To prove the hypothesis that VEO is a specialized form CPS, table 2 presents a summary of significant VEO/VEP features that can contribute in designing and implementation of CPS/Industrie 4.0.

Table 2: VEO/VEP features can contribute in Industrie 4.0 design and implantation requirements

CPS	Key Aspects	VEO/VEP features
Design requirements	Interoperability	Product self-awareness (history, status, location, delivery strategy and service)
		Throughout linking product virtual model and situational physical status.
		Resource/energy efficiency and sustainable production
	Virtualization	Empowering end users in the final product configuration.
		Generation of production and manufacturing working options.
		Accounting for time and cost.
	Decentralization	Analytics of production and manufacturing data.
		Real-time mixing of production data with engineering design data.
		User interface dynamic adaptation of information to user profile, devices, and context.
	Real-Time Capability	Emergence of new operational models
		Optimized decision making
	Service Orientation	Individualized product tracking and as underlying connection layer between factories and products.
	Modularity	Personalization and flexibility
		Dynamic resource visualization and creation of decisional footprints at the factory and machine levels.

Implantation phases	Vertical integration	Virtual environments. Virtual scenarios for new ways of planning production, especially suitable for dynamic and fast changes. Scenarios for testing different configurations
		Real-time representation of production. Visualizing flows of information, material, and knowledge in the factory, not only physical representation.
		End user interfaces. Editing configurations in demanding work conditions, such as production lines.
	Horizontal integration	Natural flow of a persistent and interactive virtual model throughout entire Product life-cycle.
		Virtual production planning by coupling of production process and product models.
	End-to-end integration	Augmented reality (AR) for process and resources/objects.
		Intelligent streaming/search to improve decision making.
		Preserving critical features for tasks while allowing interaction among VEOs.

VEO provides a structure for parts involved in the manufacturing process to possess information on themselves and suitable means of communication, and therefore themselves constitute cyber-physical systems. This VEO/VEP is to be embedded in the process as a whole and in extreme cases control not only their own logistical path through production, but rather the entire production workflow that concerns them. VEO/VEP is to supply compressed information suitably derived from the complex interrelationships and communicated in a personalized manner as the basis for their intervention in the process. In this way, a new form of cooperation between machines and parts of machines arises. This will support both short term flexibility and medium-term transformability and thus improve the resilience of production.

From table 2 it can be concluded the relation between the CPS and VEO is evident in the sense that a VEO is a kind of CPS system aiming field devices, machines, plants, and factories (even individual products) be able to store virtual living representation of themselves in the network. Thus VEO/VEP is like a black box of object/process, which has flexible and dynamic structure, having plug and play kind interface. They form a network of talking products which make machine-to-machine communication possible.

5. Conclusions

In this paper, concepts of Industrie 4.0, CPS and VEO/VEP are reviewed. It is found that virtual simulation of products and processes is one of the key aspect to achieve CPS for Industrie 4.0. It is established that VEP/VEO is experience based modelling and simulation of manufacturing processes/objects, it covers all the critical information of process planning/artefacts. Moreover this knowledge representation refers to the fact that the virtual and physical dimensions coexist and are synchronized in time, thus can be significant for the cyber physical systems. VEO/VEP can be unobtrusively overlapped with both the physical objects and the simulation model, as it addresses both the product and process levels for parts, machines and factories. Furthermore, VEO/VEP readily copes with self-organizing production and control strategies; this is a strong linking instance of product life-cycle management, industrial automation and semantic technologies. Thus, VEO is as a specialized form CPS and similarly VEP is related to CPPS.

References

1. Posada J, Toro C, Barandiaran I, Oyarzun D, Stricker D, de Amicis R, et al. Visual Computing as a Key Enabling Technology for Industrie 4.0 and Industrial Internet. Computer Graphics and Applications, IEEE. 2015; 35(2):26-40.
2. Kyoung-Dae K, Kumar PR. Cyber-Physical Systems: A Perspective at the Centennial. Proceedings of the IEEE. 2012; 100(Special Centennial Issue):1287-308.
3. Hermann M, Pentek T, Otto B. Design Principles for Industrie 4.0 Scenarios: A Literature Review 2015 07/04/2015. Available from: http://www.snom.mb.tu-dortmund.de/cms/de/forschung/Arbeitsberichte/Design-Principles-for-Industrie-4_0-Scenarios.pdf.
4. Lee E. Cyber Physical Systems: Design Challenges. University of California, Berkeley, 2008 Contract No.: Technical Report No. UCB/EECS-2008-8. Retrieved 2008-06-07.
5. Lui Sha, Sathish Gopalakrishnam, Xue Liu, Wang Q. Cyber-Physical System: A New Frontier. In: Jeffrey J. P. Tsai PSY, editor. Machine Learning in Cyber Trust: Springer. p. 3-12.
6. Henning Kagermann WW, Johannes Helbig. Recommendations for implementing the strategic initiative INDUSTRIE 4.0 2013 [01/04/2015]. Available from:

http://www.acatech.de/fileadmin/user_upload/Baumstruktur_nach_Website/Acatech/root/de/Material_fuer_Sonderseiten/Industrie_4.0/Final_report__Industrie_4.0_accessible.pdf.
7. Consortium II. Fact Sheet 2013 [cited 2015 07/04/2015]. Available from: http://www.iiconsortium.org/docs/IIC_FACT_SHEET.pdf.
8. Max Blanchet, Thomas Rinn, Georg Von Thaden, Thieulloy GD. INDUSTRY 4.0 The new industrial revolution How Europe will succeed. Think Act [Internet]. 2014 01/04/2015. Available from: http://www.rolandberger.com/media/pdf/Roland_Berger_TAB_Industry_4_0_20140403.pdf
9. The German Standardization Roadmap Industrie 4.0: VDE ASSOCIATION FOR ELECTRICAL, ELECTRONIC & INFORMATION TECHNOLOGIES; 2013 [06/04/2015]. Available from: http://www.dke.de/de/std/documents/rm%20industrie%204-0_en.pdf.
10. Lee EA. Cyber-Physical Systems - Are Computing Foundations Adequate? In Position Paper for NSF Workshop on Cyber-Physical Systems: Research Motivation, Techniques and Roadmap; Austin, TX2006.
11. Wang Y, Vuran MC, Goddard S. Cyber-physical systems in industrial process control. SIGBED Rev. 2008; 5(1):1-2.
12. Drath R, Horch A. Industrie 4.0: Hit or Hype? [Industry Forum]. Industrial Electronics Magazine, IEEE. 2014; 8(2):56-8.
13. Baheti R, Gill H. Cyber Physical Systems. In: Samad T, Annaswamy AM, editors. The Impact of Control Technology: www.ieeecss.org; 2011.
14. Annunziata PCEaM. Industrial Internet: Pushing the Boundaries of Minds and Machines 2012 [06/04/2015]. Available from: http://www.ge.com/docs/chapters/Industrial_Internet.pdf.
15. Shafiq SI, Sanin C, Szczerbicki E, Toro C. Implementing Virtual Engineering Objects (VEO) with the Set of Experience Knowledge Structure (SOEKS). Procedia Computer Science. 2014 //;35 (0):644-52.
16. Sanin C, Szczerbicki E. Set of Experience: A Knowledge Structure for Formal Decision Events. Foundations of Control and Management Sciences. 2005; 3:95-113.
17. Sanin C, Szczerbicki E. Decisional DNA and the Smart Knowledge Management System: A process of transforming information into knowledge. In: (Ed.) AG, editor. Techniques and Tools for the Design and Implementation of Enterprise Information Systems. New York: IGI Global; 2008. p. 149–75.
18. Sanín C, Mancilla-Amaya L, Haoxi Z, Szczerbicki E. DECISIONAL DNA: THE CONCEPT AND ITS IMPLEMENTATION PLATFORMS. Cybernetics and Systems. 2012 2012/02/01; 43(2):67-80.
19. Sanín C, Mancilla-Amaya L, Szczerbicki E, CayfordHowell P. Application of a Multi-domain Knowledge Structure: The Decisional DNA. In: Nguyen N, Szczerbicki E, editors. Intelligent Systems for Knowledge Management. Studies in Computational Intelligence. 252: Springer Berlin Heidelberg; 2009. p. 65-86.
20. Chen WL, Xie SQ, Zeng FF, Li BM. A new process knowledge representation approach using parameter flow chart. Computers in Industry. 2011 1//; 62(1):9-22.
21. Shafiq SI, Sanin C, Toro C, Szczerbicki E. Virtual Engineering Object (VEO): Toward Experience-Based Design and Manufacturing for Industry 4.0. Cybernetics and Systems. 2015 2015/02/17; 46(1-2):35-50.
22. Shafiq SI, Sanin C, Szczerbicki E. Set of Experience Knowledge Structure (SOEKS) and Decisional DNA (DDNA): Past, Present and Future. Cybernetics and Systems. 2014; 45(02):200-15.
23. Shafiq SI, Sanin C, Szczerbicki E, Toro C. Using Decisional DNA to Enhance Industrial and Manufacturing Design: Conceptual Approach. In: Jerzy Świątek LB, Adam Grzech, Zofia Wilimowska, editor. Information Systems Architecture and Technology; 22 – 24 September 2013; SZKLARSKA PORĘBA, POLAND. Wrocław: Wrocław University of Technology, Wrocław; 2013. p. 23-32.
24. Shafiq SI, Sanin C, Szczerbicki E, Toro C. Decisional DNA Based Framework for Representing Virtual Engineering Objects. In: Nguyen N, Attachoo B, Trawiński B, Somboonviwat K, editors. Intelligent Information and Database Systems. Lecture Notes in Computer Science. 8397: Springer International Publishing; 2014. p. 422-31.
25. Shafiq SI, Sanin C, Szczerbicki E, Toro C. Virtual Engineering Objects (VEO): Designing, Developing and Testing Models. In: A Grzech LB, J. Swiatek, Z. Wilimowska, editor. System Analysis Approach to the Design,Control and Decision Support. Wroclaw: Wroclaw University of Technology Press; 2014. p. 183-92
26. Sanin C, Toro C, Haoxi Z, Sanchez E, Szczerbicki E, Carrasco E, et al. Decisional DNA: A multi-technology shareable knowledge structure for decisional experience. Neurocomputing. 2012 7/1/; 88(0):42-53.
27. Shafiq SI, Sanin C, Szczerbicki E, Toro C. Virtual Engineering Objects: Effective Way of Knowledge Representation and Decision Making. In: Barbucha D, Nguyen NT, Batubara J, editors. New Trends in Intelligent Information and Database Systems. Studies in Computational Intelligence. 598: Springer International Publishing; 2015. p. 261-70.
28. Platform Industry 4.0. Cyber Physical Production Systems (CPPS). [01/04/2015]. Available from: http://www.plattform-i40.de/glossar/cyber-physical-production-systems-cpps.
29. P2P Foundation. Cyber-Physical Production Systems. [01/04/2015]. Available from: http://p2pfoundation.net/Cyber-Physical_Production_Systems.