Dynamic Lean 4.0 Cyber-Physical System for Polymeric Products Manufacturing in Industry 4.0

D-S Ionel and C Gh Opran

University Politehnica of Bucharest, 313 Splaiul Independentei, 060042, Bucharest, Romania

E-mail: sorin.ionel@gmail.com

Abstract. In the polymer products industry, the adoption of the intelligent production system offers solutions to increase automation and reduce the complexity of manufacturing processes. Simultaneously with the emergence and development of the Industry 4.0 concept and techniques, numerous approaches have appeared in order to implement Lean principles and tools at the intelligent production system level, with the main purpose of increasing efficiency and eliminating waste. Lean 4.0 architectures rely on the physical and digital resources of Industry 4.0, which can be active (directly involved in the production processes of the product) and passive (which have a supporting role). The implementation of Lean 4.0 principles is based on Lean 4.0 tools, defined at cybernetic level, and on the corresponding physical assets, which intervene in the management of the production flow. The objective of this paperwork is to present the realization and implementation framework of the cyber-physical system Lean 4.0 at the manufacturing cell level into an Industry 4.0 production system.

1. Industry 4.0

Advanced manufacturing technologies and latest development in communication and information technology have led to increased performance of manufacturing systems and production environment. These developments have been incorporated into the Industry 4.0 concept, which is considered the new industrial revolution. According to this concept, by integrating advanced technologies at the value chain level, a higher level of productivity and economic performance is achieved [1].

The Industry 4.0 concept is applicable by defining the cyber-physical system (CPS), which encompasses the physical production system resources, their digital representation and the cybernetic system that allows interconnection and integration of intelligent and cognitive capabilities. The CPS design involves advanced technologies embedded in sensors, actuators, the Industrial Internet of Things (IIoT) platform, newest communication systems capabilities and the latest developments in collecting and processing big data [2]. The CPS description highlights the physical space, represented by the physical objects, the processes and the environment to be supervised and controlled, the cyberspace, which refers to information, services and decision-making units, as well as the IT infrastructure, which connects these two spaces and which includes IIoT, Internet of Services (IoS) and network communication technologies (equipment, devices, computer applications, protocols, programming or communication languages) (figure 1) [3].
The CPS implementation allows transparency of information and decisions decentralization, which are the main features of structured and intelligent manufacturing systems, who allow processes real-time monitoring at the cyber system level, formulates and apply decisions at the physical system level, but also cooperation between value chain participants. Also CPS technologies allow real-time production flow changes, according to customer needs and preferences [4].

For each digitally defined physical element or assembly at the CPS level, a holon is created (a structure that behaves simultaneously as a system and subsystem). To be implemented, holons needs to be complemented by agents and functional blocks (FB). The agent is a standalone software application which represents a physical or logical object of the defined system, capable of acting independently or interacting with other agents. FBs are also software applications that incorporate commands and algorithms needed to perform a task through the logical controller. At the Industry 4.0 level, agents are the Asset Administration Shells (AAS). By adopting AAS and FB technologies, CPS becomes suitable for collecting, storing, processing data, as well as for applying emerges decisions at the physical level of manufacturing system (figure 2). In this way, CPS reacts to environment changes (becomes adaptive and flexible), the system becomes proactive, autonomous and interact or cooperate with other CPD, and learning algorithms can be applied. Thus, CPS becomes a holoarchy (a hierarchical group of holons), this feature extending to the entire production system, which allows it to be fully or partially integrated into other holoarchies [5]. The CPS main component is the Asset Administration Shell (AAS), which is a standardized digital representation of an physical manufacturing resource and has the role to achieving interoperability between different applications that manage the manufacturing system. It allows the identification of the resource, integrates the operating models and technical descriptions of its functionality [5].

Figure 1. Holistic view of cyber-physical systems [3].
Figure 2. Robot Holon, example [5].

The AAS application can represent products, machines, equipment, manufacturing systems or production subsystems at the cybernetic system level [6]. AAS consists of a header and a body. The header includes information for communication with external systems, also for identification and functionality of subcomponents. The body integrates the operating models of the asset, which can be descriptions, applications or references to other components. Each model has its own header that is part of the body manifest. While the header is standardized, which allows the integration of AAS at CPS level, the operation modules are organized as digital object memories (DOMe) that refer to an aspect, function or digital component defined at CPS level (figure 3).

Figure 3. DOMe Model [8].

These DOMs are managed at the component manager level, which allows the loading of useful modules at the level of the manufacturing CPS [7]. This AAS modules organizing method provides a data model for sharing and a framework for storing CPS data. DOMe includes a unique identification code in the form of a URL (Uniform Resource Locator), which is a reference for both instances of the asset (physical and digital representation), and allows the asset data to be stored on a dedicated server [8]. In this way, the information included in the memory model of the represented object (OMM) is not
limited by the storage space and is organized in blocks that are accessed according to the workload plan. These blocks are defined by a header containing the unique ID, and the description, which is included in a table of contents (ToC), and includes the description of the relationships between objects. OMMs also allow the ontological relations definition at the DOMe level through Resource Description Framework (RDF) and Web Ontology Language (OWL) standards, organized in a triple (subject, predicate and object), represented by URI and a declaration of validity [8]. The importance of organizing the operating models of an AAS in this way lies in the fact that they can be semantically processed and digital libraries can be set up, organized in databases, from which the OMM model can be extracted where the predicate is specific to the use case or for a particular relationship between objects, without extracting the entire content. Thus, the OMM library will be included in a modularized server, who will run a combination of components, depending on the desired manufacturing application (figure 4) and which can be accessed locally or remotely, if the data storage is distributed [8].

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![Figure 4. OMM Server components [8].](image)

This type of AAS architecture definition provides the necessary level of abstraction to define a digital manufacturing system configuration in which its elements are interconnected, flexible and self-adaptable. In this scenario, the role of AAS is to control the manufacturing physical components, as a semantically defined software application, who provides a solution in relation to the variation, specificity and specialization of machines, according to different standards under their operating functions are applied. The AAS ability to nest software components or other AASs, allows CPS functionality in different layers, the distribution of capabilities for querying, collecting and processing data and information, as well as organizing the information flow in a two-layer architecture, control plan (by AAS) and the data plan, which can be connected directly to a network of servers [7].

2. Lean Manufacturing 4.0

The dynamics of the polymer products industry have guided companies' efforts to identify the most efficient manufacturing management methods to achieve the desired competitiveness. The production objectives have been oriented the manufacturing systems towards the principles described in the Lean Management concept in order to respond to the market complex requirements, to performance continuous improvement and to increase flexibility. The adoption of Lean Management principles and Lean Manufacturing (LM) techniques have improved performance by increasing productivity, increasing quality, eliminating losses and creating value for customers [9].

The Industry 4.0 concept development underline similarities with LM in areas such as decentralization, transparency or flexible manufacturing structures, common tools and manufacturing management techniques [9]. One of the recent theories related to adaptive production systems is Lean Automation (LA), whose compatibility with the Industry 4.0 concept is ensured by a common set of fundamental technologies that can be implemented at the level of LM tools [9]. These technologies provide the data needed to measure Industry 4.0 performance indicators and matrices for evaluating
LM indicators, such as takt time, cycle time of production, lead time, work in progress, waiting, motion time, the one-piece flow rate, the workload, quality index. The implementation of CPS at LA level results in a Lean 4.0 production system, and leads to a flexible, transparent, self-managing system that eliminates non-value-added activities, with stable production cycles and a high level of standardization [10]. In order to achieve Lean Manufacturing 4.0 production system, it is necessary to separate the manufacturing resources actively involved in the production process from the passive ones, which have a supporting role within the manufacturing subsystems. In this way, the technologies and services necessary for Lean 4.0 intelligent manufacturing are selected, and the manufacturing system are being updated at CPS level with the physical and digital elements that need to be changed according to the production scenario, including with the specific LP tools [11].

This forms a technological layer that acts as an interface dedicated to the management of active resources of the production process, which is defined at the cyber level by the sum of AASs that form CPS. These AASs include applications, codes and routines that allow to embed additional instructions necessary both to operate from an Industry 4.0 perspective and to define and implement LM4.0 principles and tools. These tools are defined as Lean AAS (LAAS), which are applied to CPS processes through the instructions contained therein. LAAS tools will be grouped and managed through a meta-LAAS, defined by the requested production situation and which will assess the evolution, determine and transmit in real-time to the cyber system the adjustment commands, for interpretation and to be applied to the physical system through the function blocks [11]. An Lean 4.0 tool is conditioned by a complex set of factors distributed across product manufacturing process, depending on relevant key manufacturing performance. Defining Lean 4.0 tools is done through a specific LAAS who contains DOMe related to internal references of active or passive AAS and the instructions stored in ToC. Each AAS involved in production process incorporates DOMe Lean blocks who manage or measure performance of supervised physical asset (figure 5).

**Figure 5.** Lean Poka-Yoke tool [12].
In this way, Lean tools are applied at the manufacturing cell level, parameters are checked, deviations are corrected and will be actualized according to manufacturing scenario, with new instructions, incorporate applications, and applied different algorithms [12].

3. Dynamic Lean 4.0 CPS for Polymeric Products Manufacturing in Industry 4.0

The architecture of a polymer product manufacturing system, according to the principles of Lean Manufacturing 4.0 and Lean Automation is based on defining the physical and digital resources actively involved in the production process, at CPS level, according to the Industry 4.0 concept. The basic structure of CPS is AAS, which ensures interoperability and horizontal and vertical integration by standardizing and communicating the parameters, functions and characteristics of physical assets at the level of the cyber system. This is achieved by the intrinsic characteristics included in the header, as well as by defining the operating modules contained in the AAS body. Defining the functional modules as DOMe and organizing the information about the asset represented in the form of WMO, allows to structure them in digital libraries, which can be distributed across several databases and storage media. Through semantic processing, CPS becomes a dynamic and flexible structure, which uses only the operating modules relevant to the manufacturing situation and the production process, extracted from the manufacturing system databases, which can also be a distributed structure, locally, in the cloud or mixed. The databases characteristics and properties allow, by query and export, to generate of simplified database tables, that can include only the data necessary to define a specific CPS for each product that will be produced. Also, defining of Lean 4.0 instruments is made at the AAS level selected for specific CPS by embedded modules, specific to the resources involved to the manufacturing process (figure 6). These modules are accessed from sub-databases, generated and integrated according to the specific manufacturing scenario CPS. Each Lean 4.0 tool will nest distributed modules, call functions, collect information and formulate decisions necessary for self-optimization and self-management of the manufacturing sistem.

Figure 6. Dynamic Cyber Physical Framework for Manufacturing Lean 4.0 System.
4. Conclusions
The new elements of this paperwork are offered by the proposed solution for creating a dynamic CPS, which is flexible and adaptable to each manufacturing situation of polymeric products, and who incorporates solutions to define a Lean Cyber Physical System that preserves the necessary dynamic characteristics and allows the application of Lean Manufacturing principles, individualised on planned manufacturing processes.

5. References
[1] Salkin C., Oner M., Ustundag A., Cevikcan E. 2018 Industry 4.0: Managing The Digital Transformation. Springer International Publishing Switzerland.
[2] Mohanta B., Pragyan Nanda P., Patnaik S. 2020 Management of V.U.C.A Patnaik S., New Paradigm of Industry 4.0. Internet of Things, Big Data & Cyber Physical Systems Springer Nature Switzerland AG.
[3] Yao X., Zhou J., Lin Y., Li Y., Yu H., Liu Y. 2019 Smart Manufacturing Based on Cyber-Physical Systems and Beyond, Journal of Intelligent Manufacturing 30(8), 2805-2817.
[4] Dasgupta J. 2020 Imparting Hands-on Industry 4.0 Education at Low Cost Using Open Source Tools and Python Eco-System, in Patnaik S. New Paradigm of Industry 4.0. Internet of Things, Big Data & Cyber Physical Systems. s.l.: Springer Nature Switzerland AG.
[5] Wang L., Wang X.V. 2018 Cloud-Based Cyber-Physical Systems in Manufacturing. Cham, Switzerland: Springer International Publishing AG.
[6] Boss B., Lin S. 2018 Digital Twin and Asset Administration Shell Concepts and Application in the Industrial Internet and Industrie 4.0, https://www.iiconsortium.org, accessed 01.05.2021.
[7] Tantik E., Anderl R. 2017 Potentials of the Asset Administration Shell of Industrie 4.0 for Service-Oriented Business Models., Procedia CIRP 64, 363 – 368.
[8] Haupert J. 2014 OMM: A Structure Model for Digital Object Memories (DOMe), https://www.w3.org/2014/02/wot/papers/haupert.pdf, accessed 01.05.2021.
[9] Satoglu S., Ustundag A., Emre Cevikcan E., Durmusoglu M.B. 2018 Lean Production Systems for Industrie 4.0, in Ustundag A. Cevikcan E. Industrie 4.0: Managing The Digital Transformation. s.l.: Springer International Publishing Switzerland, 43-59.
[10] Ghouat M., Haddout A., Benhadou M. 2021 Impact of Industry 4.0 Concept on the Levers of Lean Manufacturing Approach in Manufacturing Industries, IJAME 8523 – 8530.
[11] Ionel D.S., Opran C.G., Vâlimareanu B.C. 2020 Lean Manufacturing 4.0 - dynamic physical and cybernetic system for Industrie 4.0 IOP Conf. Series: Materials Science and Engineering 916, 10.1088/1757-899X/916/1/012048.
[12] Ionel D.S., Lamanna G., Opran C.G. 2021 Lean 4.0 Dynamic Tools for Polymeric Products Manufacturing in Industrie 4.0, Macromolecular Symposia 396, https://doi.org/10.1002/masy.202000316.