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# A conceptual framework elements for Digital Twin deployment in production systems domain

Xeniya Pystina<sup>\*</sup>, Lilia Gzara<sup>\*</sup>, Vincent Cheutet<sup>\*</sup>, Aicha Sekhari<sup>\*\*</sup> <sup>\*</sup> INSA Lyon/DISP lab, Lyon, France <sup>\*\*</sup> Universite Lumiere Lyon 2/DISP lab, Lyon, France

xeniya.pystina@insa-lyon.fr, lilia.gzara@insa-lyon.fr, vincent.cheutet@insa-lyon.fr, aicha.sekhari@univ-lyon2.fr

*Abstract* — The Digital Twin (DT) as a virtual representation of physical assets aims to support transition to smart manufacturing and Industry 4.0. Today, DT remains challenging to implement on production systems because of its original technical complexity, various functions and purposes. Recent researches are focusing on Asset Administration Shell, a promising concept allowing a systemically defined and semantically described components to form distributed interoperable systems according to Industry 4.0 principles. The paper explores benefits of Asset Administration Shell and Model-Based Systems Engineering approaches to provide a conceptual framework of DT implementation in production systems.

#### I. INTRODUCTION

Most companies are interested in the transition to Industry 4.0 (I4.0) by rationally distributing existing capacities and implementing new solutions in full compliance with established requirements [1]. With the development of Internet of Things and advanced analytic tools, businesses may now use new optimized economic models based on easily accessible data from the field in order to gain in various parameters and in productivity in general. Concerning manufacturing sector and manufacturing systems in particular, the Digital Twin (DT) as an I4.0 representative is of big interest since 2003 both for researchers and practitioners [2]. Defined by ISO 23247 series as a virtual representation of a physical entity, DT is characterized by level of convergence and real-time synchronization between virtual and physical systems. Constantly growing level of complexity of manufacturing systems requires more human capacities for control, optimization and decision-making [3]. One of important DTs roles depending on its architecture is to accurately and reliably assist human in these processes, adding flexibility compared to conventional static manufacturing execution systems [4]. Given that, there is no unique DT for any physical system. The typical applications for manufacturing show the scope of DT's deployment. In this research, we focus on DT for systems. We are addressing production DT implementation methodology while considering the above-mentioned specificities.

The theoretical base, i.e. conceptualization of the term [4]–[6], formed to date allows to delve into the detailed development of the implementation methodology and practical deployment of DTs on different levels of complexity [7]. Following that, the arising generalized question is *how to build DT according to physical system* 

*characteristics and digitalization objectives.* To answer this question, a conceptual framework for DT implementation, based on various criteria, is needed.

The recent proposition made by [8] is focused on systematization of existing DT applications. The current gaps in DT, well-defined in [7], cover theoretical and practical aspects of the DT deployment on the component, system and system of system levels. Among them, the question of - how to deploy complex DT for existing production system to assure control, optimization, planning and scheduling, virtual commissioning, predictive maintenance and related decision-making processes with the possibility for easy upgrade - remains partially unsolved despite numerous attempts. The DT abilities to accumulate and operate the time dependent knowledge alongside with failure resistance during operation are under development for every specific application. The similar issue highlighting the lack in genericity of the implementation approach has been already brought up in [9] in application to reconfigurable manufacturing systems (RMS). Based on RAMI 4.0 reference architecture, which ensures interoperable distributed networks creating flexible machines, services and systems [10] and aims to establish a framework particularly for manufacturing domain, DT fits in currently on-going second digitalization phase of Industry 4.0 (I4.0) paradigm and can be further developed to become exhaustive virtual representation for production systems thanks to its similar to real world physical rules and properties [11]. Despite the fact that multiple studies tend to understand DT as a multi-tool software platform, the DT's characteristics and properties, defined in [12]-[14], reflect its modular polyvalent nature as a technology and a scientific concept. According to various reviews [2], [3], [14], the use cases for DT in smart manufacturing and production systems aimed to improve one or several specific functions or attributes of production systems already constructed and operated. However, in order to explicitly fulfill the requirements of I4.0, it is necessary to represent a consistent whole for production system DTs (i.e. their components and functions), that is to say how pieces are fit together. For this, it is important to define a conceptual framework for DT implementation taking into account system dimension and model-based system representation including, for example, analytic and verification models.

The paper is organized as follows: Section 2 gives an overview on the problem statement and related works introducing main concepts to form the framework. The proposition of framework components based on previous part is given in Section 3. Section 4 introduces the application of the proposed approach to define a DT for an academic technological platform, based on which the conclusions are in Section 5.

#### II. PROBLEM STATEMENT

The goal of this section is to provide a state-of-the-art on DT for production systems and define relevant research areas for conceptual framework elements.

The following query "digital twin and (manufacturing system<sup>\*</sup> OR production system<sup>\*</sup>) and (conceptual framework OR framework)" and (\* manufacturing), applied to the search in Web of Science for English written articles dated from 2015 to 2022, resulted in 175 sources. Focusing on the connection between DT, cvberphysical production systems and model-based systems engineering, the following network of clusters was identified (cf. Fig.1): Red - DT and Industry 4.0 generalized reviews; Blue - Industry 4.0 implementation case studies; Violet - Manufacturing case studies focusing on DT models for product design; Orange - DT Data aspects related studies; Brown - Decision-making processes for DT; Green - Industrial use cases for CPPS and smart manufacturing; Grey - DT related applications based on advanced analytics technologies; Pink -Simulation for DT related studies.



Figure 1. Clusters in DT research domain for production systems

Then 43 articles including DT frameworks, models, architectures were investigated forming the dependencies between terms (cf. Fig.2).



Figure 2. DT research domain for production systems

The results characterise DT from different sides: physical interrelations between production systems components, IIoT data exchange, data and information evaluation, digital modelling for production system virtual representation, simulation for production planning optimisation use cases and decision-making services using data analysis technologies. Then, it is possible to distinguish the following approaches for production systems:

- 1. RAMI 4.0 and ISA-95 based multi-layered frameworks including 5C architecture for cyber-physical production systems (CPPS) [15], [16];
- 2. ISO 23247 based conceptual architectures e.g.[17];
- 3. Modelling and simulation based frameworks [18];
- 4. Multi-agent systems and service systems architectures [19];
- 5. MBSE for shop floor DT [20],[21];
- 6. Conceptual frameworks with asset administration shell based architectures and interoperable frameworks [22].

Certain propositions [23], [24] use bottom-up systemic approach to explain how DT can be implemented identifying the following dimensions: the physical entity, the virtual entity, the services module, the digital twin data module, and connection module. In [25] the DT is represented in bottom-up multi-layered architecture in correlation with an automated process control systems. The global understanding of DT as an information system also finds a basis in multi-layered architectures consisting for example: in [26] of system layer - information processing layer - physical layer and model layer; in [27] of six layers where the realization of the solution is technology oriented. The top-down methodology of building DT presented in [28] focuses on decisionmaking and the main roles of DT rather than technological aspects which provides a broad view on the specificities of DT requirements and industry context. Based on the multi-agent system framework for DT, in [19], the example on system of system level implementation is provided. Authors defend the transformation of rigid architecture for production systems to multi-agent nets governed by DT service system. Currently, the structure level of shop floor prevails in scientific sources in manufacturing domain. The variety of approaches include systems engineering which indirectly relate the DT into an information system with corresponding technology [16], infrastructure [29], RAMI 4.0 that explains the relationship between users and assets on different functional levels [10]. In [20] the approach resemble to top-down system engineering development methodology. This methodology is widely implemented for shop floor DT. However, it does not fully answer to the interoperability requirement for DT and define the global objective for the system. The DT system design based on DT metamodel is provided in [21], where authors use MBSE for top-down physical system design and highlight the difficulty to represent all physical system knowledge in DT metamodel. Authors in [30] conclude that different intelligent manufacturing applications can be developed using RAMI 4.0

framework securing the standardization for implementation, communication protocols and control.

Finally, a wide range of DT design methods form a rich theoretical base for system design and drive production system domain to a new stage of development. The bottom-up implementation approach has its limits when it comes to a complex asset such as production systems due to increasing amount of data from asset components. At the same time starting to define the asset from use case objective can be beneficial in cost for new development and renovation. The reasons for renovations are of great concern especially for the existing solutions. The cases related to modernizations cannot fully answer to DT requirements and therefore cannot be referred to DT. The cases that harmonize two approaches are limited and refer to asset and system level, whereas the use cases on system of system level are missing. The main contribution is that for DT application the proposed approach associates the MBSE methods bidirectionally from business to physical levels of RAMI 4.0.

#### III. PROPOSITION

The necessity to consider DT comprehensively from behavioral, informational and technical aspects can be supported by MBSE formalized methodology, digital models, as well as asset administration shell standardized specification and software. The proposition for implementation procedure is the following sequence: definition of the main objective (in the framework of RAMI 4.0 and domain standards), metamodel definition (relationship between main instances), definition of related services to support objective (including simulation, synchronization and visualization), then connection to the external DT. At the same time, the asset characteristics and its DT's functionalities will pass the verification and validation through the development methodology. Each component of the proposed approach is explained below.

#### A. Model-based system engineering approach

Systems engineering and its derivative MBSE is able to involve every aspect of the production system and pay attention to interfaces when two or many systems or their elements are working together using representing models. The vision to understand DT as a system of systems provides large opportunities in cross-domain and specific applications in manufacturing. The INCOSE System Engineering Handbook defines the "Systems of Systems" as "an interoperating collection of component systems that produce results unachievable by the individual systems alone". According to ISO/IEC 15288 "the perception and definition of a particular system, its architecture and its system elements depend on an observer's interests and responsibilities". Therefore, the DT inherits different functions and characteristics reflecting those from the systems it constitutes. The interoperability issue is at the core of I4.0 needs. The stated role of interoperability is to synthesise, connect and communicate software components, business processes application solutions through a diversified and

heterogeneous and autonomous procedure [31]. DT through MBSE ensures this interaction between systems on different functional and hierarchical levels of RAMI 4.0 using models as referential. Consequently, the standardized models and specifications help to overcome growing complexity of models and transit to interoperable solutions and continuously facilitate data flows as an example of Asset Administration Shell. To analyze functional and non-functional requirements of DT, the SysML language is used while descending on RAMI 4.0 hierarchical levels [32]. In addition, it is intended to complement existing domain-specific tools by providing a system view with which domain-specific views must remain consistent. Following the methodology from [33], the requirements definition for future DT system should be identified. The diagram



Figure 3. Context diagram for requirement analysis process [33]

(Fig.3) represents the requirement analysis process that could be applied to identify and specify DT in order to propose the conceptual framework and DT architecture for production systems.

It defines functional and performance requirements as well as architectural constraints and verification criteria for the system. The objective is to characterize the DT system context describing the environment in which it operates as well as different entities for interaction, i.e. users and other systems. By identifying different interactions of the system, the context diagram will help identifying the input/output flows that the system exchanges and also the interfaces required to achieve these interactions.

#### B. RAMI 4.0 for production system applications

The reference architecture unites three different dimensions represented by three axes: "The life cycle and value stream" for product lifecycle management supported by ISO 62890; the layers axis to represent functionalities of the product; the hierarchy levels retrieved from IEC 62264/IEC 61512. RAMI 4.0 defines system architecture with respect to aforementioned dimensions and represent the framework for I4.0 applications in manufacturing domain. The asset characteristics can fully be described by RAMI 4.0 on different levels from business to physical.

#### C. Asset Administration Shell

The AAS is a well-used application in automation domain forming an effective solution for data and information management and interoperability capabilities thanks to its semantic identification support. Defined as a digital representation for assets, the AAS structures the data from the physical world using system engineering approach. The standardized meta model of AAS is aimed to create interoperable DTs with respect to the structure and reduce the design efforts for data organization. In addition, AASs of existing products provide a base for product-as-a-service business models, where information can be stored during the product lifecycle and used by different parts.

However, the use cases applying AAS to production system DTs are still few, due to the complexity of data flows, the rights' policies and security issues of different components vendors. The possible benefits can be achieved not only in interconnectivity and interoperability capacities in xml file exchange but also as an information aggregation source and a buffer between enterprise resource planning systems, SCADA and control systems. The developers for AAS present its 3 possible roles or interaction patterns: as a metadata specification, as an API for DT services and for active interconnected DT [34]. These options maintain a standardized approach and transform systems to I4.0 components. [35] claims that AAS provide limited support in DT content determination entirely up to its developers. Nevertheless, the proposed approach eliminates this inconsistency.

#### D. DT development process

The development process we propose for DT systems implementation can be organized from system and operation architectures design and system evaluation to technical coordination and system integration. The important stages (Fig.5) in system logic development start with objectives and constraints identification (Step 1) and dependent from the key events in production process.



Figure 4. RAMI 4.0 application procedure

Based on that, main scenarios can be developed defining working tasks and schedule packages (Step 2). DT system is in charge of decision, configuration and information management processes. RAMI 4.0 does not restrict the complexity level of the information systems moreover organizes the structure for implementation process. Following the hierarchy level axe of RAMI 4.0 from use cases referring to a connected world it is

possible to identify critical asset from other potential assets among the components of production system for future DT (Step 3). The question is where a DT for the assets that are not yet manufactured can be referenced to a definition of the digital mock-up therefore for existing production systems the DT works on the operation/production lifecycle stage until the end of the life. The collected information totally depends on the use case.

Therefore, the DT development process includes the following steps: 1) The objective definition and related performance indicators; 2) The information source - assetidentification; 3) DT system requirements identification in connection with an asset; 4) DT modelling (functional, logical architecture and structure) and analysis; 5) Evaluation and verification. The possibility to use standardized specification and AAS model to organize knowledge about physical asset and at the same time structured MBSE approach to identify corresponding functional and non-functional DT system characteristics will provide more stable solution easy to upgrade with new elements and related properties.

#### IV. APPLICATION

In this section the first steps of the systems engineering approach that enables to define an architecture for production system DT is presented. The application case



Figure 5. Robot filling the pallet with jetons on assembly post

concerns the flexible production line on the AIP-PRIMéca Academic Technological Platform - Industry 4.0 S.mart RAO (Fig.5). The seven working posts of the line ensure the continuous production process of pallets filled with jetons according to the requested production order. The assembly and disassembly posts are equipped with industrial robots which are of main interest.

The procedure (Fig.6) starts from the "work centers" hierarchical layer for production line instead of omitted "enterprise" layer. For the production line on the "business" layer, the global objective is defined with assigned KPIs for value estimation corresponding to various missions or scenarios. For example, "rescheduling" mission for a specific station of the line.



Figure 6. System engineering approach application on RAMI 4.0

Consequently, various decisions could be made at functional level depending on thetasks that are assigned to the station, e.g. "detection".

In order to define the information from the data, the product is identified with unique identifier for each product component. On integration and communication layers the raw data transfer is assured by control devices forming control system, OPC-UA communication protocol and RFID reader. Meanwhile, the production order previously generated and recorded on the pallet RFID tag can be rescheduled pointing the specific asset. The asset layer concerns the product itself, the jetons and all components of the system involved in process.



Figure 7. Initial requirements for DT of the working unit

In order to specify components on functional layer of RAMI 4.0, the starting point to understand the DT system can be illustrated by DT requirements for the assembly post of the production line (Fig.7). The global objective defines the assembly process requirements controlled by DT of the post. The same logic can be applied to other posts equipped with industrial robots. The assembly scenario is controlled by the DT of the assembly post. The system DT will federate DT of the stock and DT of the posts by data exchange. The requirements mirror the physical assets which are the industrial robot, the production line and the product consisting of pallet and jetons. Assuming the fact that the DT system has its own life cycle the diagram may be developed further.

#### V. CONCLUSION

The proposed approach considers the DT as a system and correlates the existing I4.0 reference architecture with systems engineering elements, to constitute the conceptual framework. This latter is based on information that describes production system, production process, assembly orders, product and resources. Further, the system can be enriched by additional information concerning maintenance. The framework aims to provide a view on an operational and logical problem description. To represent DT functionalities on RAMI 4.0 layers with the help of models, the important aspects of modelling should be taken into account. For example, for decisionmaking - the cross-domain and domain specific ontology, for functions organisation - metamodel entities and relationships and for time scheduled system supply semantically identified data. The next step is establishing the functional architecture of DT where the system functions and their interconnection are identified. For this step, the inputs and outputs of the system as well as its functions are needed. Moreover, the functional architecture represented by activity diagram should include DT decision-support module.

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