DOI: 10.2478/aucts-2018-0002

ACTA UNIVERSITATIS CIBINIENSIS – TECHNICAL SERIES
Vol. LXX 2018

A REVIEW OF RECENT REFERENCE ARCHITECTURES FOR CYBER-PHYSICAL SYSTEMS, IN THE INDUSTRY 4.0 ERA

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Abstract: *With the uptake of the IoT in the industrial domain, a whole new range of cyber-physical systems has emerged; Industry 4.0 is the title given to this technological domain of highly interconnected, data-rich systems. To aid the development of such systems, a range of reference architectures has been developed throughout the years. This paper reviews a number of recent reference architectures, detailing their essential traits as well as identifying aspects that need to be further explored in order to obtain reference architectures better tuned to generating cyber-physical social systems.*

Key words: cyber-physical systems, reference architectures, state of the art

1. Introduction

Cyber-Physical Systems (CPS) are central to current industrial efforts of establishing an Industry 4.0 working regime. One key challenge of achieving such an objective is that of designing effective reference architectures (RA) that will ensure the cross-collaboration and inter-operability of industrial systems, on a local or even global scale. Challenges also relate to the development of architectures for enterprises that possess other qualities of being a Future Internet-Based Enterprise [1]; examples are humanistic enterprises, inventive enterprises or cognisant enterprises, concepts which are all to be strived for.

Recent years have seen a wide range of reference architectures being proposed, by consortia or research projects striving for extracting and synthesizing architectural principles required to meet the challenges defined above. This paper presents the state of the art in terms of RAs for CPS corresponding to the Industry 4.0 domain. In doing so, the paper is structured as follows: Section 2 details the state of the art, Section 3 provides a discussion on the reviewed RAs, while Section 4 details the conclusions of this article.

2. State of the Art

In this section, we will present a number of relatively recent RAs that reflect the state of the art of this domain. The RAs will be listed in chronological order, with the oldest RA being presented first.

2.1. IoT Reference Architecture

The Internet of Things – Architecture project[1] produced a comprehensive document **[2]** that not only defines a RA for CPS, but also details the underlying architectural reference model (ARM), while also providing guidance for using the RA in order to generate specific architectures. The work itself, while being extensive (500 page document) is not complete e.g. the information model is only partially defined; still, the ARM contains eloquent descriptions of the domain, functional and communication model which a CPS would need to implement.

The IoT-RA complies with the framework of already established architectural views and perspectives, such as those denoted in **[3]**. Key to its description are the concepts of (IoT) service and Virtual Entity (VE); the architecture is centred on the definition of various types of services (IoT-level, enterprise-level, VE-level), which expose computational resources; in addition, the services may be associated with VEs, so that the real world is mirrored into the digital world (CPS), as shown in Figure 1.

[1] https://cordis.europa.eu/project/rcn/95713_en.html

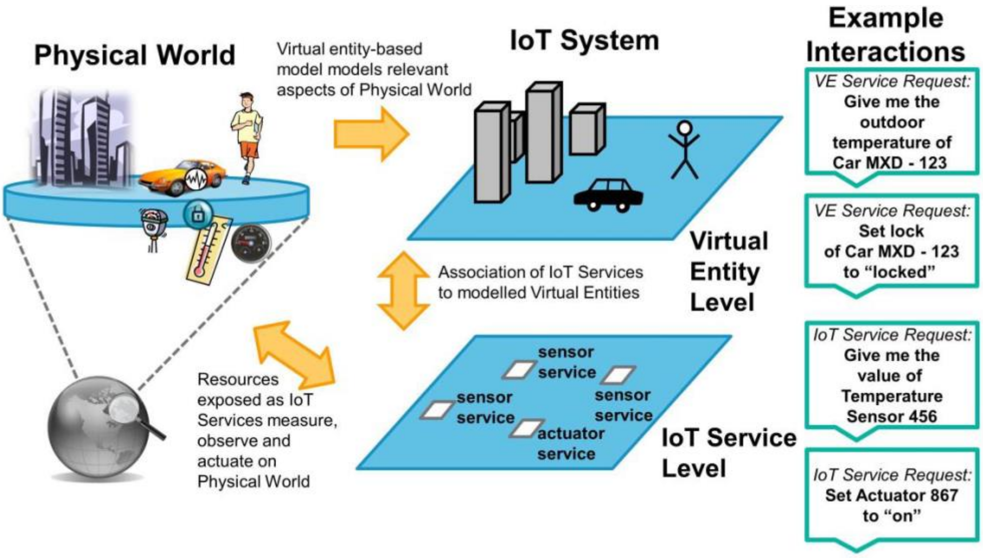

Figure 1: IoT Service and VE abstraction levels [2]

The overall approach is techno-centric: the RA is composed of Functional Groups (FG) and Components, with the user interacting with the system via the top-level Applications Functional Group. Figure 2, describes, using UML formalism, the functional model of IoT-RA: the bottom two components (the Devices and Communication FG) are not explicitly addressed by IoT-RA; on top of the Communication FG resides the IoT Service FG which identifies the IoT services made available in the enterprise, while also providing functions for discovering, looking-up or managing service descriptions; further above we find FGs dedicated to the design and execution of IoT processes (the IoT Process Management FG), to the composition, orchestration and choreography of services (the Service Organisation FG) and also to resolution, monitoring and editing of VEs (the Virtual Entity FG); top of it all is the Application FG, through which users can interact with the system.

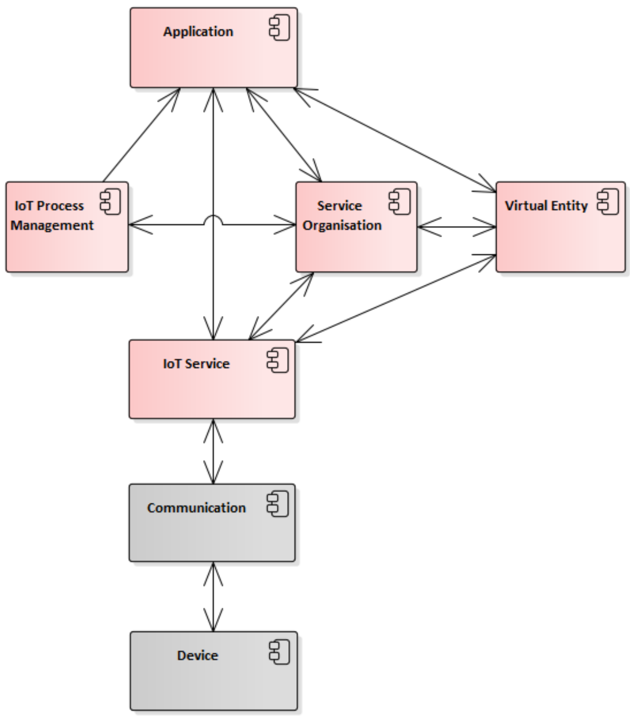

Figure 2: UML diagram representing IoT-RA's Functional Groups (part of the functional model)

2.2. *FITMAN Reference Architecture*

The FITMAN project[2] delivered three RAs **[4]** that define the main components of smart, digital and virtual enterprises. The three types of enterprises reflect, actually, three levels of abstraction: a) the shop floor, which becomes "smart" due to the addition of IoT technologies, b) the office floor layer of an enterprise,

[2] https://cordis.europa.eu/project/rcn/109803_en.html

which is enhanced by "digital" software systems for analysis, planning, design, etc. activities and c) the upper layer of the interconnected supply-chain, which is seen as a "virtual" enterprise because, through the use of Internet technologies, all parties are more aware of and can better collaborate with each other.
Figure 3 exemplifies, using UML formalism, FITMAN's Virtual Enterprise reference architecture, which is focused on "assuring inter-company communication, integration, collaboration and interoperability, as well as on managing tangible and intangible assets" **[4]**. The central point in this architecture is the Legacy systems component, through which users interact with the web of interconnected companies (top layer) and their own legacy systems. In between the Legacy system component and the external companies there is a specialized interface called the Enterprise Interoperability and Collaboration Layer, which boasts functions providing support for cooperative business process design and management, thus assuring cross-enterprise boundaries interoperability and collaboration. In addition, relevant data pertaining to tangible and intangible assets involved in virtual factory business processes, is discovered, classified and managed via the Enterprise Tangible/Intangible Assets Management Layer.

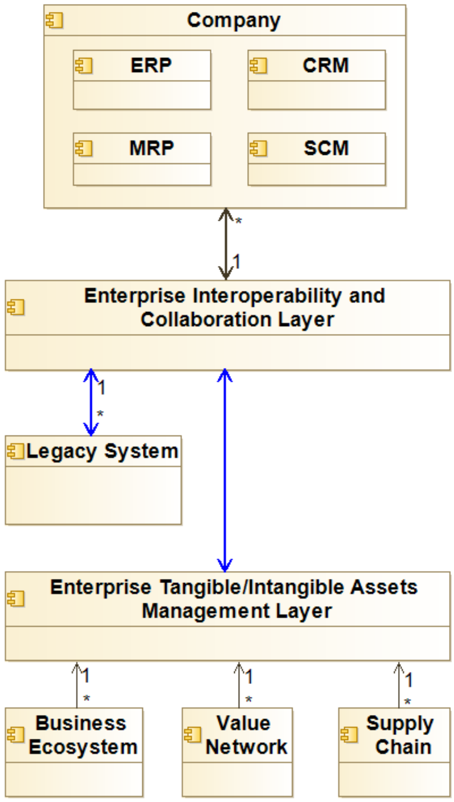

Figure 3: UML representation of FITMAN's Virtual Factory reference architecture

2.3. OSMOSE Reference Architecture

The OSMOSE project delivered a RA **[5]** **[6]** intended to enable the development of sensing-liquid enterprises, as defined by the FInES Research Roadmap 2025 **[1]**; these two qualities represent a subset of the nine[3] qualities of being (QB) of Future Internet-based Enterprises. Key to the OSMOSE RA is the identification of three worlds (real, digital and virtual) to which an enterprise's assets belong; communication between worlds is mediated by a "membrane", which allows osmotic processes to take place (information entering the membrane is processed and routed to the other worlds according to complex event processing and knowledge links mechanisms). These osmotic processes are grouped in three feedforward/feedback pairs, representing the mediated interaction between the three worlds. Figure 4 provides a UML representation of the OSMOSE RA, with its worlds, membrane and inter-world processes.

[3] The nine qualities of being (QB) are: 1) Humanistic Enterprise, 2) Inventive Enterprise, 3) Agile Enterprise, 4) Cognisant Enterprise, 5) Sensing Enterprise, 6) Community-oriented Enterprise, 7) Liquid Enterprise, 8) Global Enterprise and 9) Sustainable Enterprise.

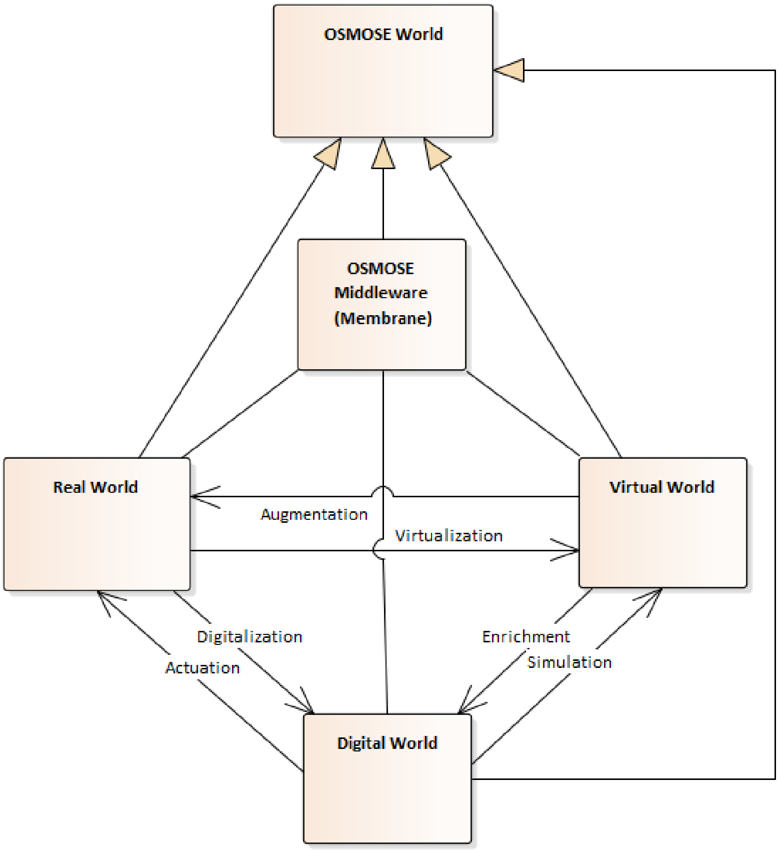

Figure 4: UML diagram of OSMOSE main concepts (worlds, membrane and interaction processes)

The OSMOSE reference architecture details the types of components that make up each world as well as the membrane. Essentially, we're dealing with a service-oriented architecture, which is enhanced by the use of a distributed knowledge-base (with common and world-specific ontologies) and semantic as well as complex event processing capabilities.

2.4. Industrial Internet Reference Architecture

More recently, the Industrial Internet Consortium (IIC) delivered the industrial Internet Reference Architecture **[7]**, which is strongly based on the ISO/IEC 42010 **[8]**. In fact, the IIRA instantiates ISO/IEC 42010 for the Industrial Internet domain, selecting four relevant viewpoints[4] and detailing the elements that need to be defined in order to generate views for each viewpoint. For example, the business viewpoint requires an architectural description to define the stakeholders relevant to the system, their vision, values, the system's key objectives as well as fundamental capabilities; the usage viewpoint prescribes the definition of all parties, roles and the tasks and activities (flows of tasks) they may execute. From a functional point of view, IIRA requires the description of the control domain, together with the, operations, information, application and business domains. Implementation wise, the IIRA specifies architectural patterns (i.e. topologies for interconnecting physical devices or logical layers within an enterprise) that may be applied when constructing specific system architectures.

In addition, the RA defines a number of crosscutting concerns (similar to Rozansky's perspectives **[3]**), which cut across (need to be considered) all four viewpoints. These concerns are split into crosscutting functions (connectivity, industrial analytics, intelligent and resilient control, etc.) and emergent system characteristics (safety, security, resilience, reliability, privacy, scalability, etc.). Figure 5 is a good, albeit incomplete, representation of the IIRA.

[4] A business, a usage, a functional and an implementation viewpoint.

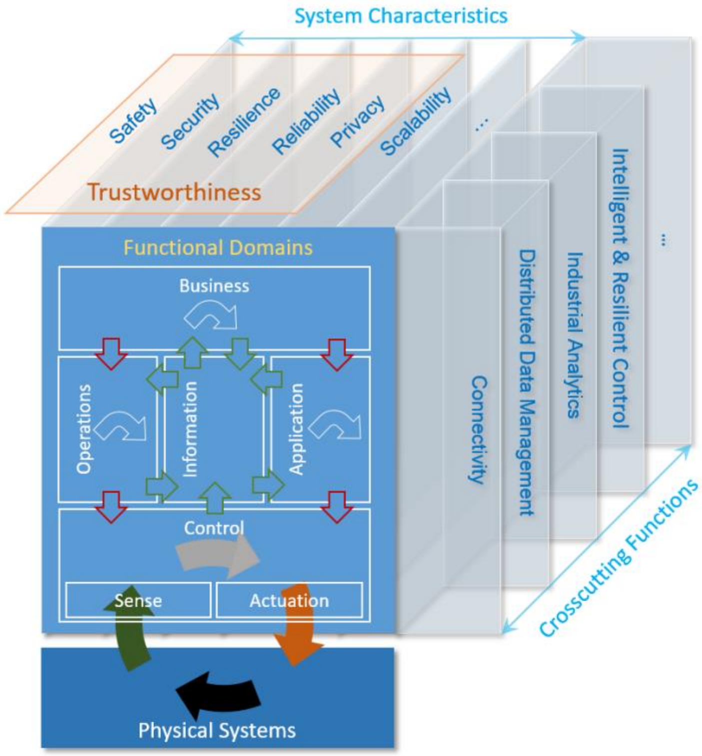

Figure 5: Functional Domains, Crosscutting Functions and System Characteristics [7]

2.5. BEinCPPS Reference Architecture

In a similar timeframe, the BEinCPPS project finalized its RA, oriented on cyber-physical production systems (CPPS). While initially the BEinCPPS RA **[9]** was a combination of the OSMOSE and RAMI 4.0 RAs, the final version **[10]** adopted a simplified and more structured approach, that makes use of four perspectives in order to define a multi-layered reference architecture.

The first layer is BEinCPPS RA's structural perspective, which divides the elements of a CPPS into design-time and runtime, while runtime systems are considered at different hierarchical levels. Following is the functional perspective; here the BEinCPPS RA proposes a number of functional blocks, superimposed over the structural perspective, and a flow of information between them. Next is the technical perspective, which identifies technical standards that must be supported in key functional blocks. Finally, the implementation perspective identifies assets or defines components that implement the functionality required by the functional blocks. Figure 6 presents the functional perspective, as proposed by the BEinCPPS RA.

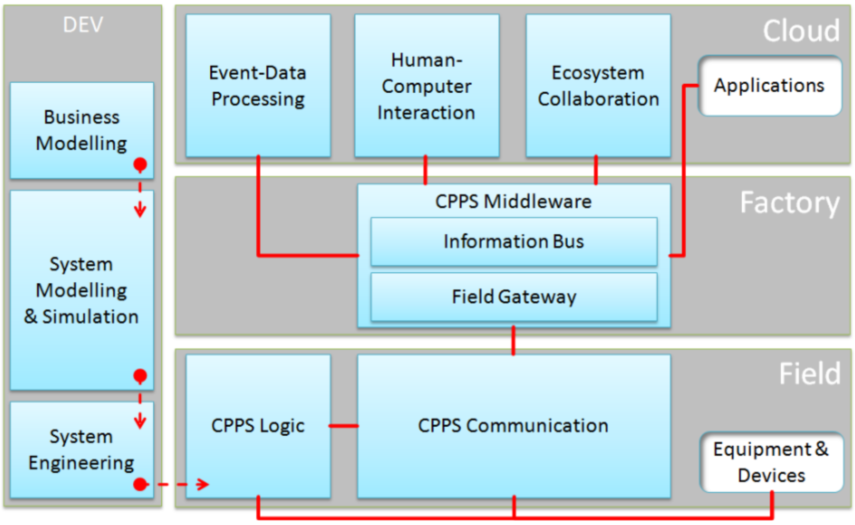

Figure 6: BEinCPPS' functional perspective [10]

2.6. RAMI 4.0

The Reference Architecture Model Industrie 4.0 (RAMI 4.0) is an RA based on a multi-dimensional understanding of semantic technologies and automation capabilities, which facilitate the development of a new kind of intelligent industry, named Industrie 4.0 (I4.0). The foundation of RAMI 4.0 is its three-dimensional reference model **[11]**, which extends the Smart Grid Architecture Model, while also building on international stands such as IEC 62264.

Figure 7 presents the RAMI 4.0 model. Its three dimensions define the following aspects of an Industry 4.0 system: a) its layers (types of subsystems that make it up) b) its lifecycle and value stream and c) its hierarchical levels.

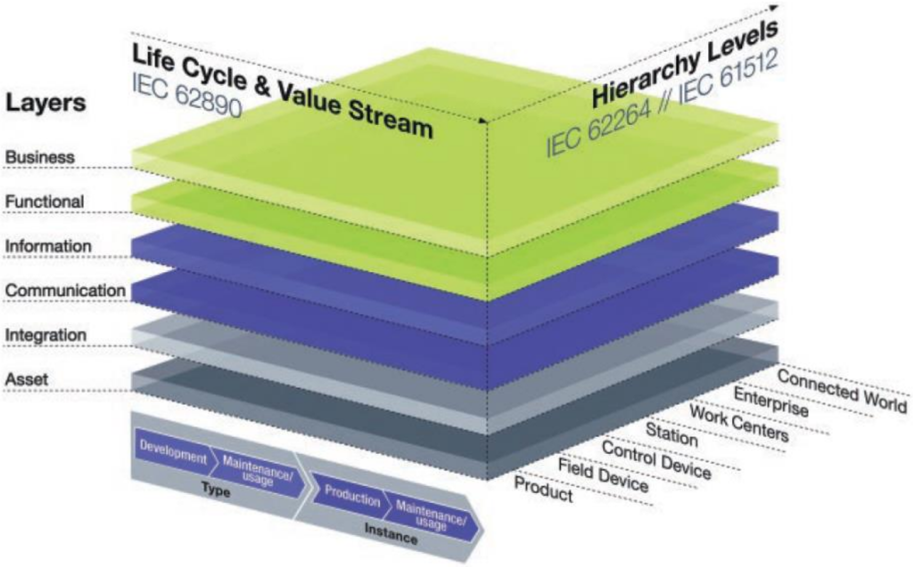

Figure 7: RAMI 4.0 reference architecture [11]

At the centre of RAMI 4.0 is the concept of I4.0 component. Any asset capable of passive communication can be transformed into an I4.0 component, through the use of an Administration Shell. The Administration Shell is implemented as an independent data/function object, which can be hosted on the asset itself (if it has I4.0 communication capabilities) or on a higher level IT system, as part of an I4.0 Component Repository. Figure 8 provides a UML representation of the RAMI 4.0 architecture based on the use of I4.0 components.

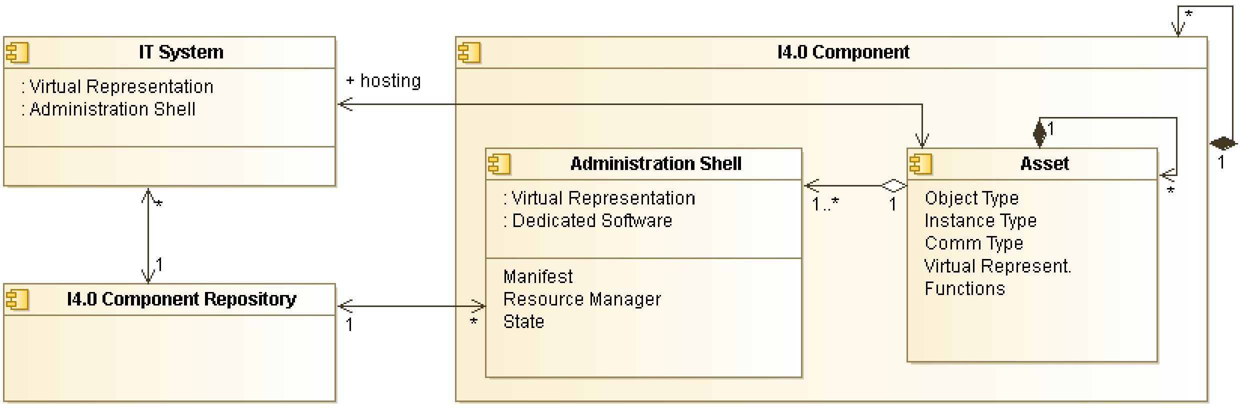

Figure 8: UML representation of the RAMI 4.0 architecture

3. Discussion

The RAs presented in the previous section reflect relevant efforts that were made in order to obtain a baseline for developing enterprises belonging to the Industry 4.0 domain or to the Future Internet-Based Enterprises. There is great diversity in the composition of these RAs, in the level of detail with which they are described, as well as in the scope that they have. Table 1 provides a brief comparison of these RAs.

One common trait that we identify in the mentioned RAs is that they are mostly techno-centric. For example, in the FITMAN RAs, humans are identified as end-users that only control the system from a logically remote location; in the OSMOSE RA, the human user is only considered in terms of the data and multimedia information the system stores for or about him, or in terms of "avatars" that may be used in "what-if" simulations pertaining to the virtual world; in the BEinCPPS RA, humans are also just application users, much like the IoT-RA. Explicit references to the importance of the social dimensions are made in the IIRA (where the business and usage viewpoints are detailed), in ISO/IEC 42010 and RAMI 4.0, but there is still room for improvement.
For the above reasons, we find that there is room for improvement in terms of defining RAs that not only consider the technical dimension, but also put focus on integrating the human element as a central actor in the control loop.

Table 1 General information about the reviewed reference architectures

Reference Architecture	Publication year	Intended system	Scope
IoT-A	2013	CPSoS	General applicability
FITMAN Smart Factory	2013	Smart Factory	Shop floor
FITMAN Digital Factory	2013	Digital Factory	Office floor
FITMAN Virtual Factory	2013	Virtual Factory	Supply chains
RAMI 4.0	2015	I4.0 Enterprise	Supply chains
OSMOSE	2016	Sensing-Liquid Enterprise	Individual enterprise
IIRA	2017	IoT CPSoS	General applicability
BEinCPPS	2017	Cyber-physical production systems	Field devices, Factory, Cloud

4. Conclusions

This article has provided a brief review of state of the art reference architectures applicable to Industry 4.0 CPS engineering. Six reference architectures have been succinctly presented, not only from a structural perspective (their key constituting elements), but also from a socio-centric perspective.
The article emphasizes the fact that these RAs are of techno-centric nature. This is achieved by either focussing on demonstrating specific properties (such as OSMOSE's focus on the sensing-liquid enterprise or FITMAN's Virtual Factory which targets the inter-company collaboration layer) or by implicitly reducing the human element to that of an application or system user.

5. Acknowledgement

This work is supported by the DiFiCIL project (contract no. 69/08.09.2016, ID P_37_771, web: http://dificil.grants.ulbsibiu.ro), co-funded by ERDF through the Competitiveness Operational Programme 2014-2020

6. References

[1] FInES Research Roadmap Task Force, "Research Roadmap 2025," 2012.

[2] The Internet of Things – Architecture project, "Deliverable D1.5 - Final architectural reference model for the IoT v3.0," 2013.

[3] N. Rozanski and E. Woods, Software System Architecture, 2005.

[4] D. Rotondi, J. Benedicto, O. Lázaro, M. Sesana and S. Gusmeroli, "Deliverable D1.5: FITMAN Reference Architecture," 2013.

[5] A. Felic, C. Rubattino, G. Di Vito, C. Agostinho, C. Lucena, K. Fischer, D. Liudmila and M. Sesana, "D 3.11 - First OSMOSE Models and Architecture," 2014.

[6] A. Felic, M. Sesana, L. Dobriakova, C. Rubattino, J. Ferreira, M. Marques, K. Fischer, A. Collado, L.

Gonzalez and R. Sanguini, "D 3.12 Final OSMOSE Models and Architecture," 2016.

[7] Industrial Internet Consortium, "Volume G1: Reference Architecture," 2017.

[8] ISO/IEC/IEEE, ISO/IEC/IEEE 42010:2011(E) Systems and software engineering — Architecture description, 2011.

[9] K. Fischer, A. Jara, A. Geven, D. Rotondi, E. Coscia, L. Aştefănoaei, M. Rooker, M. Isaja, O. Botti and S. Voss, D2.1 -D 2.1a BEinCPPS Architecture and Business Processes, 2016.

[10] M. Isaja, K. Fischer, D. Rotondi, E. Coscia and M. Rooker, "D2.2 - BEinCPPS Architecture & Business Processes," 2017.

[11] P. Adolphs, H. Bedenbender, D. Dirzus, M. Ehlich, U. Epple, M. Hankel, R. Heidel, M. Hoffmeister, H. Huhle, B. Kärcher, H. Koziolek, R. Pichler, S. Pollmeier, F. Schewe, A. Walter, B. Waser and M. Wollschlaeger, "Reference Architecture Model Industrie 4.0 (RAMI4.0) - Status Report," 2015.