Available online at www.sciencedirect.com

ScienceDirect

Procedia Computer Science 180 (2021) 102–111

Procedia Computer Science

www.elsevier.com/locate/procedia

International Conference on Industry 4.0 and Smart Manufacturing

Extending the scope of reference models for smart factories

Nuno Soares[a*], Paula Monteiro[ab], Francisco J. Duarte[a], Ricardo J. Machado[a]

[a]*ALGORITMI Research Centre, University of Minho, Campus de Azurém, Guimarães 4800-058, Portugal*
[b]*CCG/ZGDV Institute, Campus de Azurém Edifício 14, Guimarães 4800-058, Portugal*

Abstract

Industry 4.0 (I4.0), Smart Manufacturing, Industrial Internet, Intelligent Manufacturing, and so forth, are different designations for different initiatives, all contributing to the digital transformation of the industrial ecosystem. Besides several reference models/architectures have been developed, a framework to structure and understand the implications and to identify I4.0 action fields is still needed. A harmonized model would allow guiding the developments on how to organizationally prepare for the change. This paper attempts to clarify the implications and action fields of the I4.0, trying to reveal its mostly alleged dimensions and the main planes in which they intervene in the industrial ecosystem. Through the analysis of the most relevant architectures for I4.0, IoT and Cyber-Physical Systems (CPS), and the consequent awareness of which components are missing, the paper proposes a framework for digital factories towards smart cities that stresses the expansion of the I4.0 horizontal integration into human, cities infrastructural, and societal dimensions.

Keywords: Reference Model; Reference Architecture; Smart Factory; Industry 4.0; Iot; CPS; Smart Manufacturing; Smart Cities

1. Introduction

The increasing integration of Internet technologies and concepts into the industrial ecosystem has built the foundation for the 4^{th} industrial revolution. Among the different initiatives and designations, I4.0 is perhaps the most identifiable with the use of the Internet of Everything in industrial organization, but even the key promoters of the idea, the Industrie 4.0 Working Group [1] only describe the vision, the basic technologies the idea aims at, and selected scenarios, not providing a clear definition. As a result, a generally accepted understanding of I4.0 has not been published so far, hindering an I4.0 transformation.

* Corresponding author. *E-mail address:* nuno.soares@algoritmi.uminho.pt

10.1016/j.procs.2021.01.134

Furthermore, several reference architectures have been developed for the industrial digital transformation, they diverge on the focus and dimensions, what causes indecision and uncertainty on transformation efforts.

This paper tries to clarify the implications of the I4.0, trying to reveal its mostly alleged dimensions and the main planes in which they intervene in the industrial ecosystem. Supported on a critical review of the most relevant models and architectures for I4.0, IoT and CPS, the paper analyses the diversity of components suggested by the various proposals and catalogue them under several planes, proposing a five-planes harmonized reference model for smart factories. Beginning with the manifestation of the major benefits of a reference model for smart factories, Section 2 summarizes the motivation for this work recognising the nonexistence of a unified reference model and the motivation to pursue one, describes the literature research and the criteria to include or exclude the reference models and architectures for smart factories. Section 3 describes the selected models distinguishing them in two major groups with a different value for modelling the entire ecosystem of a digital factory. Section 4 describes the analysis performed for the selected models, the identification and the collecting of the dimensions for the overall models selected, and the resulting proposal of classification for grouping these dimensions under dimensional planes, accommodating them in a smart factories reference model based on that classification. Facing the results, a critical analysis of these models is described, including the dimensions they combine, the extent of the planes they describe, and the relative importance they devote to each of them. Common and individual gaps are identified for all models studied and to cope with these gaps, the section ends proposing and justifying a linkage with the other major playground for digital transformation - the smart cities universe - established precisely from the human and societal planes that the study showed to be the most neglected in the architectures reviewed. Section 5 concludes with remarks about the undertaken work and some considerations for future work.

2. Methodology

A reference architecture guides the development of system, solution and application architectures. A unifying high-level abstraction of these architecture patterns and descriptions has noticeable benefits since it provides common and consistent definitions, patterns, and a collective vocabulary, that facilitates easy sharing experience and know-how in designing, implementing and operating the systems [2] [3], in a way that encourages reuse of common system building blocks [2] [4], reduces the risk through the use of proven and partly prequalified architectural elements [2], provides better quality by facilitating the achievement of quality attributes [5], provides guidance to technology vendors to build market-fitting system components and those that are interoperable and applicable to multiple industrial sectors, and contributes to the overall interoperability of the different systems [2] [4].

Responding to the realization of how beneficial such architectures are to model the complex systems of systems of smart factories, several proposals have been advanced. Several reference architectures have been developed for the industrial digital transformation, however diverging on the focus and dimensions included, what causes indecision and uncertainty on transformation efforts. There is no unique and unified model for the industrial ecosystem, neither a model that covers by itself all the planes that should be addressed.

Literature was surveyed taking into account the identification of all the reference architectures that could contribute by incorporation, for the formulation of a harmonised model for smart factories transformation, resulting from the sum of these existent architectures, and pinpointing the dimensions and its overall planes.

The increasing integration of the IoT into the industrial value chain builds the foundation for the smart factories. The same can be said about the CPS, a larger entity than the IoT and much intertwined, sometimes even confounded with it.; i.e., the IoT is a network/communication subset of CPS, that is the implementation of the IoT in a physical system. With this in mind, the inclusion criteria comprised reference models addressing the manufacturing environment as a whole, but also reference models exclusively for IoT which can be exploited in an industrial environment, and other reference models or architectures narrower and even more specific, which refer exclusively to the use of CPS in industry.

SCOPUS and Google Scholar were surveyed with variations of similar terms and expressions around Industry 4.0 (I4.0, Industrie 4.0), Internet of Things (IoT, Industrial Internet, IIoT), Cyber-Physical Systems (CPS, CPPS), and reference models (reference model and reference architecture). Article search was performed since the year of 2011, the appearance of the Industry 4.0 concept, to late 2019. Screening citations on the examined articles left space for further exploration of papers missed in the initial search. Beyond the selected databases, well-known worldwide institutions and authorities related to industrial and manufacturing environments and standards development organizations (SDO) were assessed, since this research topic has been of interest to both academia and industry. A snowballing process was also performed reviewing the references of the articles to find other potential primary studies.

This research work refers to surveying reference models and not papers describing them. So, hundreds of sources and articles were found, which together refer to only seventeen different models presented in the next section. Two major principles guided the analysis of the surveyed reference models: an attempt to identify the similar components, and a confrontation with the dimensions involved in the reference models being proposed for smart cities, which are another current related digitalisation initiative.

3. Reference models for smart factories

This section describes the selected reference models and architectures and divides them into two groups. Models for the entire ecosystem of a factory (Group A), and models for the IoT and/or CPS based specific models (Group B).

3.1. Models for industry

The Reference Architecture Model Industry 4.0 [6], from Plattform Industrie 4.0, groups four distinct aspects in a common model. The vertical integration within the factory describes the networking of means of production. The end-to-end engineering throughout the value stream that means the technical, administrative and commercial data of a means of production or of a workpiece are kept consistent within the entire value stream and can be accessed at any time via the network. The horizontal integration via added-value networks extends beyond individual factory locations and facilitates the dynamic creation of such added value networks. And, finally, the human being as a conductor for added value, orchestrating the value streams.

The Plattform Industrie 4.0 intended that a three-dimensional model is best suited to represent the I4.0 space. In the vertical axis the IT thinking layers, ranging from Asset in the lowest level to Business in the topmost, including in this order: Integration, Communication, Information, and Functional. In the leftmost horizontal axis, the Product life cycle with the value streams, following IEC 62890 from development/production to maintenance/usage and divided between Type and Instance. And, in the third and rightmost horizontal axis, the representation of the hierarchy levels with the location of functionalities and responsibilities within the factories/plants.

The RAMI 4.0 functional layer contains services that support the business processes and provide functional access to physical assets (e.g. factory plant, machinery, sensors, actuators, mechanical parts, etc). In RAMI 4.0, an asset compounds an I4.0 Component, which has two parts: the asset, and the asset's administration shell.

The Industrial Internet Reference Architecture (IIRA) is a standards-based architectural template and methodology enabling the design of Industrial Internet of Things (IIoT) systems [7] [8]. This reference architecture from the Industrial Internet Consortium (IIC) explicitly identifies four separate but interrelated sets of concerns and points of view: the business viewpoint, the usage viewpoint, the functional viewpoint, and the implementation viewpoint [9].

IIRA specification identifies also a three-tier IIS Architecture with an Edge Tier, a Platform Tier, and an Enterprise Tier, with three different networks connecting the tiers: Proximity Network, Access Network, and Service Network. These tiers play specific roles in processing the data flows and control involved in usage activities. The edge tier collects data from the edge nodes, using the proximity network. The platform tier receives, processes and forwards control commands from the enterprise tier to the edge tier. The enterprise tier implements domain-specific applications, decision support systems and provides interfaces to end-users including operation specialists. The three-tier architecture pattern combines major components (e.g. platforms, management services, applications) that generally map to the functional domains defined in the functional viewpoint.

In IIRA also intends that are common concerns that cannot be assigned to a particular viewpoint or to one of the functional domains described above. Addressing these concerns requires consistent analysis across the viewpoints and concerted system behaviours among the functional domains and components, ensured by engineering processes and assurance programs. IIRA name these special topics as key system concerns:

IIRA is seeking answers in multiple industry domains, such as energy, transportation, and manufacturing. In this respect, IIRA steps off from the precedent RAMI that is only concerned about the entire value chain of the manufacturing. IIRA developed more than twenty testbeds that represent specific use cases where industrial internet technologies are being applied to demonstrate real-world industrial internet solutions implementations.

The NIST model, Smart Manufacturing Ecosystem (SME) [10] deals with a broad scope of manufacturing systems including business, production, management, design, and engineering functions. SME identifies and generates a smart manufacturing systems landscape of standards pinpointing whether, where, when and for what purpose the standard could be used among the manufacturing ecosystem, particularly in which point of the three axes: product, production, enterprise (business), or in the pivotal manufacturing pyramid.

In product axe, the product lifecycle ranges from design, process planning, production engineering, manufacturing, and use & service, to End of Life (EOL) & recycling. The information flows and controls along the product lifecycle are wholly concerned. In the production axe, the production system lifecycle spans from design, build, commission, and operation & maintenance, to decommission & recycling. These lifecycle phases are mainly about an entire production facility including its systems. In the business axe, the supply chain cycle extents from plan, source, and make, to deliver & return, which mainly addresses the functions of interactions between supplier and customer. The pivotal manufacturing pyramid (based on IEC/ISO 62264, previously ISA 95) is where the axes converge and interact, including in a strictly bottom-up enunciation, device level, supervisory control and data acquisition (SCADA) level, manufacturing operations management (MOM) level, and enterprise-level, which represents the vertical integration of machines, plants and enterprise systems.

Industrial Value Chain Reference Architecture (IVRA) is the structure of manufacturing defined by the Japanese government Industrial Value Chain Initiative (IVI). The IVRA has three independent layers that supplement one another: Specification, Activity, and Business [11]. IVRA delivers two truly novel concepts, the Smart Manufacturing Unit (SMU) which describes an autonomous unit of smart manufacturing, and the General Function Blocks (GFB). An SMU, an System of Systems (SoS) that faces diversity and individuality of industrial needs, usually resembles an enterprise or a smaller unit, as long as it has people who manage its internal structure and be able to modify itself when needed. It is composed of three axes: Asset, Activity, and Management.

The asset view of an SMU shows assets, properties of the SMU that are valuable to the manufacturing organization: personnel, product, plant, and process assets, and some of them can be transferred between different SMUs as needed. The management view shows purposes and indices relevant to management, like assets and activities appropriately steered in terms of quality, cost, delivery and environment. The activity view covers the activities performed by SMUs at manufacturing sites in the real world, which can be viewed as a dynamic cycle continuously improving targeted issues proactively: "Plan, Do, Check and Act”.

Intelligent manufacturing is named as the Chinese I4.0 and has several points of contact with the German Plattform Industrie 4.0. Thus, Intelligent Manufacturing System Architecture (IMSA) is the equivalent to RAMI 4.0. IMSA is a tri-dimensional system architecture that allows determining the scope of every smart manufacturing-related technology in terms of the dimensions Life Cycle, System Level, and Intelligent Functioning [12]. In IMSA, a landscape of intelligent manufacturing standardization architecture is proposed in assistance to standards classification. The landscape totally covers groups of basic standard types, key technology standard types, and industrial application standard types. As the existing standards regarding intelligent manufacturing are unavailable, undeveloped or repeated, an effort has been done to guide the intelligent manufacturing standardization, releasing several Chinese standards.

3.2. Models for Internet of Things

The IoT-ARM resulted from the IoT-A project, an EU co-founded FP7 programme, aiming to provide a generic Architectural Reference Model (ARM) that can be used to derive concrete IoT architectures [13]. The model consists of a set of views used to represent certain structural aspects of the system, and perspectives that focus on the quality of the system that spans different views, e.g. security, resilience. Its functional view proposes a layered model of functional groups, which maps to most of the concepts introduced in the domain model, together with a set of essential functional components and associated interfaces that an IoT system should provide. Between Device as the lowest group, and Application as the topmost group, are placed the remaining groups. The information view, based on the information model, complements the functional view and provides a more detailed view about how information is to be handled in the system, including details about the components where the information is handled, and how it flows within.

The International Telecommunication Union (ITU) Telecommunication Standardization Sector (ITU-T) produced a series of recommendations about IoT [14] [15]. The ITU-IoT reference model tries to establish a common grounding for IoT architectures and IoT systems and is composed of four layers as well as management and security capabilities which are associated with all the four layers.

The Application layer contains IoT applications. The Service and Application Support layer consists of common capabilities which can be used by different IoT applications and various detailed capability groupings, in order to provide different support functions to different IoT applications. The Network layer provides relevant control functions of network connectivity and IoT services and applications transportation. The Device layer includes direct/indirect device interaction with the gateway and communication network. Finally, Management Capabilities define how to manage the devices, traffic, etc, and the Security capabilities include functions related to authentication, integrity protection, privacy and security.

The first goal of the NIST Framework for Cyber-Physical Systems (FfCPS) was to derive a unifying framework that covers the range of unique dimensions of CPS [16]. It identifies domains of CPS, in which manufacturing is included. The FfCPS also identifies cross-cutting concerns, like societal, business, technical, and analyses these cross-cutting concerns producing aspects that are groups of conceptually equivalent or related concerns. Then, FfCPS address the concerns (aspects) through activities and artefacts organized within three fundamental facets: conceptualization, realization, and assurance. Facets are views on CPS, encompassing identified responsibilities in the system engineering process, and containing well-defined activities and artefacts for addressing concerns.

The W3C Web of Things (WoT) is intended to enable interoperability across IoT Platforms and application domains. It provides mechanisms to formally describe IoT interfaces to allow IoT devices and services to communicate with each other, independently of their implementation, and across multiple networking protocols, and provides a standardized way to define and program IoT behaviour. The abstract architecture for the W3C Web of Things is derived from a set of use cases, including one for the smart factory. The abstract architecture for the WoT has three levels where WoT building blocks can be applied: the device level, the gateway level (or "edge"), and the cloud level [17]. WoT also defines a conceptional architecture of the building blocks, decomposing a Thing in the containing layers: WoT Binding Templates, Interaction Model, WoT Scripting API, and Applications.

The ISO/IEC 30141 Information technology - Internet of Things Reference Architecture (IoT RA) covers the IoT in general. It defines system characteristics, a conceptual model, a reference model, and architecture views for the IoT [18]. The IoT RA Conceptual Model contains an overall model for IoT concepts plus five important IoT concepts: (1) Domains concept, (2) Identity concept, (3) Service and Communication concept, (4) IoT-User concept, and (5) IoT Device concept. ISO/IEC 30141 defines an Entity-based Reference Model and a Domain-based Reference Model. The Entity-based Reference Model shows how users, systems, networks, gateways, devices, and physical entities relate to each other. The Domain-based Reference Model shows the relations between the User, Operations and Management, Application Service, IoT Resource and Interchange, Sensing and Control, and Physical Entity domains. The five views are Usage, Functional, Information, System, and Communication.

WSO2 is an American company that provides open-source technology. The WSO2 IoT recommended architecture, consists of seven layers from a higher level to a lower level [19]: Client/external communications, including Web/Portal, Dashboard, and API Management; Event processing and analytics; Aggregation/bus layer; Communications layer; and Devices. Cisco Systems envisioned a comprehensive, multilevel model as its IoT reference model [20]. The Cisco IoT reference model proposal has seven layers. In a strictly bottom-up enunciation, the levels are 1) Physical devices and controllers, involving the Things; 2) Connectivity, responsible for communication & processing units; 3) Edge (fog) computing, containing the data element analysis & transformation; 4) Data accumulation, responsible for storage; 5) Data abstraction, concerning the functionalities of aggregation & access; 6) Application, including the building blocks of reporting, analytics, and control; and 7) Collaboration and processes, involving people & business processes.

Finally, although some models analysed can be perceived as architectures, did not express any form of dimensions, components or other similar structures, and can’t be compared and made compatible with those that explicitly pointed-out components and the relations between them. As are the cases, for instance, of Monostori Cyber-Physical

Production System (CPPS) [22], Lee 5-C architecture [23], Pérez et al. vertical integration architecture [24], and Mazak and Huemer architecture for horizontal integration [25].

4. Proposed reference model

Although the relevance of all proposals, some are more useful than others when modelling the entire ecosystem of a smart factory. IoT reference models (Group B) abstract notably but only this specific component and only the reference models and architectures that entirely represent the whole industrial phenomenon (Group A) can comprehensively provide insight, knowledge, common definitions and vocabulary, across and between all the elements.

All reference/architecture models were scrutinized and a spreadsheet was used to create an exhaustive list with all dimensions involved in each one, which facilitated the subsequent aggregation. Here, become evident that some models of the Group B that don't explicitly pointed-out components and the relations between them can't be subject to this exercise.

The decomposition operated for the dimensions pertinent to the overall industrial ecosystem showed a total of forty-two dimensions or components, even after some depuration obtained from eliminating evident synonyms and aggregating evident similar dimensions. These dimensions were sorted by affinity what made it easier to identify dimensions whose designations are very close and to associate them. Similarities and overlaps also became apparent.

Starting from this affinity expressed in the proximity with which they appear in the list, we tried to circumscribe these components in larger groupings that denote this similarity, starting from the inspiration given by some models that structure their principal dimensions under category planes. The need to characterize each of the main planes in which reference models explain their guidelines led to the definition of the categories of dimensions: cyber, physical, lifecycle, human, and comprehensive.

Table 1 presents the final definition, with the non-aggregable 24 dimensions grouped by planes. Alongside unquestionable designations such as cyber and lifecycle, less apparent ones have emerged as 'comprehensive' and 'human'.

The dimensions identified in the reference/architecture models appear in their respective plane. In some cases, given the diversity of designations for what could be considered the same or very similar dimension, the different designations were pointed out and separated by a vertical slash. An X indicates the evident presence of each dimension in the reference model/architecture.

The Cyber plane corresponds to the virtual and computable part of the industrial ecosystem. It regards the ICT dimensions, which doesn't mean that all dimensions comprising it are ICT dimensions.

The Lifecycle plane includes all kinds of lifecycles related to factories. The entire lifecycle of a product, the production system itself, the value and supply chain and the lifecycle of the services see their processes described, managed and ruled under this plane. The Physical plane congregates the production system hierarchy, ranging from Product to Connected World, in what constitutes an expansion of the hierarchy levels of IEC 62264. It contains all that is material, particularly the production system hierarchy, and also the interactions between enterprises (e.g. suppliers, business partners, sub-contractors, other business types, and other enterprise sizes). The Human plane relates to all people's activities and associates the human resource management capabilities with the innovation efforts produced by the workforce in terms of the introduction of new equipment, improved processes, or new materials. Finally, the Comprehensive plane is the cluster for all the dimensions and capabilities involved across the other planes: competences for management, security, privacy, safety, and prescription of usage that are transversal to all dimensions. Additionally, the rationale and the representation of the system architecture of the factory itself lies in this plane of dimensions.

Given the aggregation achieved, the fact that the IoT reference models (Group B) did not make new contributions to the systematization of the unified reference model, which were not already pointed out by the I4.0 reference architectures (Group A models), it is considered that the standardization efforts should be based entirely on Group A models, more complete and representing the whole industrial phenomenon, and that the human and societal components, that were identified as being the more undervalued dimensions, should be explored from these models.

Table 1. Category-organized dimensions for model propositions for smart factories.

Categories	Dimensions	RAMI	IIRA	SME	IVRA	IMSA	IoTARM	ISO/IEC 30141	FfCPS	WoT	ITU IoT	WSO2	CISCO
Cyber	Usage		x					x					
	Business	x	x		x	x			x				
	Application | Client/external comms.$^{\beta}$ | Collaboration and processes$^{\phi}$						x				x	x^{β}	x^{ϕ}
	Functional | Pyramid Enterprise Lvl$^{\beta}$ | Software Objects$^{\phi}$	x	x	x^{β}				x	x	x^{ϕ}			
	Information | Pyramid MOM Lvl$^{\beta}$ | Thing description$^{\phi}$	x	x	x^{β}	x	x		x	x	x^{ϕ}		x	x
	Communication | Pyr. SCADA Lvl$^{\beta}$ | Interaction model$^{\phi}$ | Network$^{\varphi}$	x	x	x^{β}	x	x	x	x		x^{ϕ}	x^{φ}	x	x
	Integration | Implementation$^{\beta}$ | Virtual entity$^{\phi}$ | System$^{\varphi}$ | Servients$^{\theta}$	x	x^{β}			x	x^{ϕ}	x^{φ}		x^{θ}			
	Asset | Pyramid Device Lvl$^{\beta}$ | Device$^{\phi}$ | Phys. devs & controllers$^{\varphi}$	x	x	x^{β}	x	x	x^{ϕ}	x			x^{ϕ}	x^{ϕ}	x^{φ}
	Service Organisation | Service & application support						x				x^{β}		
	IoT Process Management						x						
	IoT Service						x						
Lifecycle	Product lifecycle	x	x	x	x	x			x				
	Production system lifecycle			x	x				x				
	Supply Chain/Value Chain	x		x	x	x			x				
	Service Lifecycle	x	x	x	x								
	Meta-lifecycle	x											
Physical	Production system hierarchy	x		x	x	x							
	Enterprises Interactions				x			x					
Human	Human Resource Management	x	x		x	x			x				
	Innovation (Novelty)	x			x	x			x				
Comprehensive	Prescriptive rules of usage	x			x								
	Management capabilities						x				x	x	
	System Architecture	x	x		x	x					x		
	Support & Protection capabilities | Security capabilities$^{\beta}$	x	x	x	x	x	x	x	x		x^{β}		

The prevalence in which the human dimensions appear in this inventory seems low and limited in scope. A reference model, when modelling the industrial ecosystem, presenting its organization and the relationships between the various elements and the environment, should not ignore the environmental, human, societal, and infrastructural concerns that assist the context in which the industrial plants are located. A strong linkage to the context of the smart cities should be required and occur when the horizontal integration that underpins some of these models, extends through cities dimensions.

The horizontal boundaries of the production sites and organizations are fading as more and more business and manufacturing processes develop across them, and the distance between design, production and usage tends to disappear thanks to the increasing integration of the product lifecycle management. Policymakers and industrialists state the relevance of the human component in the novel manufacturing landscape towards I4.0 [26], [27], [28]. However, there is poor knowledge about how to design or adapt production systems taking into account human-centric perspectives and it is reflected in the current reference architectures for factories.

The seamless integration of the various stakeholders (e.g., customers, suppliers, and subcontractors) and their requirements that are characteristic of the I4.0 horizontal integration, must continue with other cities stakeholders and requirements from other cities dimensions.

Factories have their existence in cities, at least in the broader concept of cities adopted by smart cities, best embodied by regions or territory, and share many resources and restrictions with them. The employees in a factory integrate the Smart People in Smart Cities, the factories' management, transportation, and ordering, correspond to the Smart Governance, Smart Governance, Smart Mobility and Smart Economy in cities. The manufacturing activity have implications on Smart Environment, and the Smart Living is greatly determined by employees working hours. Lom et al [29] propose an I4.0 view as a necessary part of the smart cities, stressing a set of common areas that justify the union of the two concepts. ICT has the same role in I4.0 and smart cities, behaving has a key factor and acting as an enabling technology.

Soares et al. [30] reviewed existing smart city modelling proposals and synthesized them into a unified smart city reference architecture, The result is a set of dimensions organized by human (economy & business, people, education, and smart living), institutional (government & governance, safety & security, healthcare, and institutions), city-component related (transportation, urban infrastructure, smart buildings and energy) and environmental viewpoints, supported by a services provider five layers ICT framework.

In addition to the particularities of cities and factories, although these are not as disparate as that, as justified before, it seems understandable that the models for factories include, at least to some extent, these macro-perspectives present in the models for cities, that Soares et al. work [30] synthesizes by being present in most proposals of reference models for smart cities.

The ICT framework (here, the Cyber plane) is well represented and instantiated to the industrial context in most of the models for factories studied. The same does not happen with human, institutional and city-related components.

Facing this, and the above regarding the conviction for close tight smart factories with smart cities, we propose the graphical representation of the two present-day worldwide 'digitalisation enterprises' expressed in Figure 1. The figure only displays the five I4.0 reference architectures (Group A models), since given the present work it was found that they do not receive additional contributions from the remaining models. Each I4.0 reference architecture exhibits preponderance with respect to the identified planes. The choice for the planes instead of dimensions is not random and aims to emphasize that it is more important to stick with the dimension planes that specify the areas of intervention, rather than case by case with the variety of dimensions' names that need to be standardized. A larger layer represents a stratification of this plane into more dimensions, which were taken directly from the number of dimensions it has in Table 1.

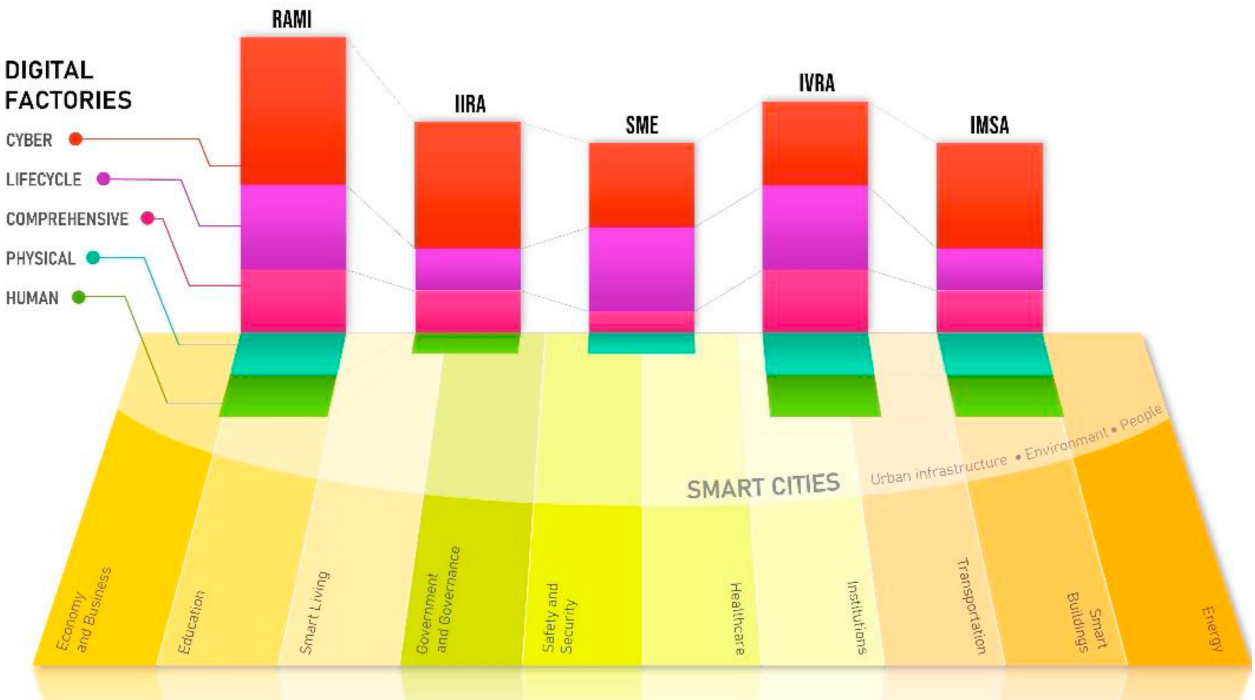

Figure 1. Extended Scope of the Reference Models for Smart Factories.

The Comprehensive category, being supportive of the other categories, is placed as a hinge, in the centre of the others, still in the vertical plane. Above it, the immaterial categories, respectively Lifecycle and Cyber. In the horizontal plane, following the Comprehensive category are the material ones: Physical and Human, both in direction and practically already in the universe considered as smart cities. The initial contact surface shall be smart cities' dimensions People, Environment, and City Infrastructure, because are the smart cities dimensions closer to our five-planes harmonized reference model for smart factories.

After these, reference models for factories and reference models for cities should tighten relationships, modelling common paths in Energy and Transportation components, just to mention the evident ones that determine how factories manage supply/value chain and power themselves. The figure illustrates from the right to the left, but not on a particular order, the following remaining smart cities dimensions identified by Soares et al. [30] that should be addressed by both, smart cities and smart factories.

5. Conclusion

This paper attempts to clarify the meaning, implications, and action fields of the I4.0, trying to reveal its mostly alleged dimensions and the main planes in which they intervene in the industrial ecosystem.

Existing smart factories modelling proposals were reviewed ranging from truly industrial ecosystem's reference architectures to IoT reference architectures, including IoT and/or CPS-based specific architectures, and synthesized into a harmonised smart factories reference architecture, contributing to the definition of the dimensions and its overall planes that must be part of such models. The result is a set of dimensions organized by four category planes transversally supported on comprehensive capabilities.

The analysis shows the preponderance of the ICT plane on these models. However, the IoT reference models and the IoT and/or CPS based specific models that deal exclusively with the technological plane, showed that they did not provide to the systematization of the unified reference model, any contribution that had not already been made by the I4.0 reference architectures.

Conversely, human dimensions receive minor attention and environmental, societal, and infrastructural concerns are out of range of these models. The fading of the factories' horizontal boundaries, as more manufacturing processes develop across them, should force the incorporation of these concerns on the reference models for factories. Some links between these two 'digitalisation enterprises' should be apparent on these architectures.

The paper proposes an extended reference model for smart factories towards smart cities, inducing a rationale on this subject and identifying the interfacing dimensions, to begin with. As future research, we recommend studies that concretize the incorporation of the smart industry in smart cities. Moreover, an all-encompassing reference architecture is also currently pursued for smart cities.

Acknowledgements

This work has been supported by FCT – Fundação para a Ciência e Tecnologia within the R&D Units Project Scope: UIDB/00319/2020 and by the Doctoral scholarship PDE/BDE/114567/2016 funded by FCT, the Portuguese Ministry of Science, Technology and Higher Education, through national funds, and co-financed by the European Social Fund (ESF) through the Operational Programme for Human Capital (POCH).

References

[1] H. Kagermann, W. Wahlster, and H. Johannes, "Recommendations for implementing the strategic initiative INDUSTRIE 4.0: Final report of the Industrie 4.0 working group," Acatech, Frankfurt, 2013.

[2] R. Cloutier, G. Muller, D. Verma, R. Nilchiani, E. Hole, and M. Bone, "The concept of reference architectures," *Syst. Eng.*, vol. 13, no. 1, pp. 14–27, 2010.

[3] G. Muller and P. van de Laar, "Researching reference architectures," in *Views on Evolvability of Embedded Systems*, Springer, 2010, pp. 107–119.

[4] M. Galster and P. Avgeriou, "Empirically-grounded reference architectures: a proposal," in *Proceedings of the joint ACM SIGSOFT conference--QoSA and ACM SIGSOFT symposium--ISARCS on Quality of software architectures--QoSA and architecting critical systems--ISARCS*, 2011, pp. 153–158.

[5] E. Y. Nakagawa, P. O. Antonino, and M. Becker, “Reference architecture and product line architecture: A subtle but critical difference,” in *European Conference on Software Architecture*, 2011, pp. 207–211.

[6] P. Adolphs *et al.*, “Reference Architecture Model Industrie 4.0 (RAMI4.0),” VDI/VDE/ZVEI, Frankfurt am Main, Germany, 2015. doi: 10.1007/s13398-014-0173-7.2.

[7] R. Herzog, M. Jacoby, and I. Podnararko, “Semantic interoperability in IoT-based automation infrastructures,” *At-Automatisierungstechnik*, vol. 64, no. 9, pp. 742–749, 2016.

[8] I. Bücker, M. Hermann, T. Pentek, and B. Otto, “Towards a methodology for Industrie 4.0 transformation,” in *International Conference on Business Information Systems*, 2016, vol. 1, pp. 209–221.

[9] S.-W. Lin *et al.*, “Industrial Internet Reference Architecture 1.8 - Volume G1: Reference Architecture,” *Ind. Internet Consort.*, 2017.

[10] NIST, “Current standards landscape for smart manufacturing systems,” U.S. Department of Commerce, National Institute of Standards and Technology, 2016. [Online]. Available: http://dx.doi.org/10.6028/NIST.IR.8107.

[11] IVI, “IVRA Next - Strategic implementation framework of industrial value chain for connected industries,” lndustrial Value Chain Initiative, Tokyo, 2018.

[12] MIIT and SAC, “National Intelligent Manufacturing Standard System Construction Guidelines (Version 2015),” Ministry of Industry and Information Technology of China, 2015.

[13] Bauer et al., “IoT-A - The final architectural reference model for the IoT v3.0,” 2013.

[14] ITU-T, “ITU-T Y.4115 - Reference architecture for IoT device capability exposure,” International Telecommunication Union, Geneva, Switzerland, 2017.

[15] ITU-T, “Recommendation ITU-T Y.2060 - Overview of the Internet of things,” International Telecommunication Union, Geneva, Switzerland, 2012.

[16] E. R. Griffor, C. Greer, D. A. Wollman, and M. J. Burns, “Framework for Cyber-Physical Systems: Volume 1, Overview,” 2017. doi: https://doi.org/10.6028/NIST.SP.1500-201.

[17] M. Kovatsch, R. Matsukura, M. Lagally, T. Kawaguchi, K. Toumura, and K. Kajimoto, “Web of Things (WoT) Architecture - W3C Editor’s Draft 22 August 2019,” 2019. https://w3c.github.io/wot-architecture/.

[18] ISO/IEC, “ISO/IEC CD 30141 - Information technology – Internet of Things Reference Architecture (IoT RA),” International Organization for Standardization/International Electrotechnical Commission, Geneva, Switzerland, 2016.

[19] P. Fremantle, “A reference architecture for the internet of things,” *WSO2 White Pap.*, 2014.

[20] Cisco Systems, “The Internet of Things Reference Model - White Paper.” 2014.

[21] L. Monostori, P. Valckenaers, A. Dolgui, H. Panetto, M. Brdys, and B. C. Csáji, “Cooperative Control in Production and Logistics,” *IFAC Proc. Vol.*, vol. 47, no. 3, pp. 4246–4265, 2014, doi: 10.3182/20140824-6-ZA-1003.01026.

[22] L. Monostori, “Cyber-physical Production Systems: Roots, Expectations and R&D Challenges,” *Procedia CIRP*, vol. 17, pp. 9–13, 2014, doi: 10.1016/j.procir.2014.03.115.

[23] J. Lee, B. Bagheri, and H. A. Kao, “A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems,” *Manuf. Lett.*, vol. 3, pp. 18–23, 2015, doi: 10.1016/j.mfglet.2014.12.001.

[24] F. Pérez, E. Irisarri, D. Orive, M. Marcos, and E. Estevez, “A CPPS Architecture approach for Industry 4.0,” in *Emerging Technologies & Factory Automation (ETFA), 2015 IEEE 20th Conference on*, 2015, pp. 1–4.

[25] A. Mazak and C. Huemer, “A standards framework for value networks in the context of Industry 4.0,” *IEEE Int. Conf. Ind. Eng. Eng. Manag.*, pp. 1342–1346, 2015, doi: 10.1109/IEEM.2015.7385866.

[26] O. Lazaro, “First Stakeholder´s Forum for the Digitising European Industry Initiative,” European Commission, Essen, Germany, 2017.

[27] EFFRA, “Factories 4.0 and beyond - Recommendations for the work programme 18-19-20 of the FoF PPP under Horizon 2020,” European Factories of the Future Research Association, 2016.

[28] European Comission, “Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions for a European Industrial Renaissance,” 2014. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52014DC0014.

[29] M. Lom, O. Pribyl, and M. Svitek, “Industry 4.0 as a part of smart cities,” *2016 Smart Cities Symp. Prague*, pp. 1–6, 2016, doi: 10.1109/SCSP.2016.7501015.

[30] N. Soares, P. Monteiro, F. J. Duarte, and R. J. Machado, “A Unified Reference Model for Smart Cities,” *Sci. Technol. Smart Cities. SmartCity 360 2019. Lect. Notes Inst. Comput. Sci. Soc. Informatics Telecommun. Eng.*, vol. 323, 2020, doi: 10.1007/978-3-030-51005-3_16.