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Reference Architectures for Industry 4.0: Literature Review

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Abstract. Currently, production systems are receiving the application of more advanced, integrated and connected technologies to optimize the performance of their manufacturing processes. The new technological solutions demand architectures that support intelligent solutions for a new digitalized industry. However, production systems already in operation have difficulty in implementing these technologies. The existing barriers limit the availability of the direct integration of different systems contemplated in an automation system architecture. This article systematically reviews the existing literature to portray the characteristics of each architecture and that can guide the adoption of new technologies. Through this review, emerging reference architectures were identified, such as RAMI4.0, IIRA, IBM Industry 4.0 and NIST Smart Manufacturing. In conclusion, the article presents a framework for considering which model best fits with the new technological solutions.

Keywords. Architecture model, Industry 4.0, reference model, smart manufacturing

Introduction

Currently, production systems are receiving the application of more advanced, integrated and connected technologies to optimize their manufacturing processes. The concept of Industry 4.0 encompasses these new technologies, such as IoT, Big Data, Analytics and others, which support new demands oriented to intelligent solutions [1].

However, production systems already in operation have difficulty implementing these technologies. Existing barriers limit the availability of directly integrating the different systems contemplated in an architecture of automation systems. Usually the communication between these existing automation systems is carried out in different layers and protocols, making the information have strong flow limitations within the working architecture. Establishing communication through all hierarchical levels of an automation platform to access process data freezes the system and makes it difficult to include intelligent systems. There are also other barriers that directly interfere with the application of new, more intelligent architectures, such as the incompatibility of communication between equipment from different manufacturers due to the existence of proprietary solutions and also the limitation of technological capacity to meet a more dynamic flow to enable a balance of performance during system operations. In many

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cases, the development of alternative solutions is necessary to enable communication between two equipment from different manufacturers.

In this sense, new technologies need to be integrated within an industrial equipment topology to directly carry out real time communication between all components of the system, enabling the adoption of intelligent solutions. The integration of a system will result a better physical configuration and functional performance and can be made possible through the application of automation architectures.

An automation architecture is a representation of the structure of a system in more detail, used for the system design, configuration of the physical assets, installation and their interfaces, specification of equipment and systems, selection of control technology, design of commands and realization of automation, communication and management functions [15]. The architecture definition process involves the search for alternative architectures or solutions within an automation platform through appropriate technological or technical elements that make up the system. This process is also used to define the requirements for each element of the system [14]. The notion of this process is abstract, but it is used to create, design or redesign products, services or companies. Designers and developers must be attentive in the choice and definition of an automation and control system, so that the project takes into account several criteria and that it can be in sync with technological advancements fulfilling the demands of new industrial solutions.

The new technological solutions demand the need for architectures that support intelligent solutions for a new digitalized industry. The present study aims to explore the architectural models already published through a systematic literature review.

1. Fundamental concepts

This chapter shows some fundamental concepts for the review, starting with the definitions of Industry 4.0 and architectural models.

1.1. Industry 4.0

The term Industry 4.0 appeared in mid-2011, during the Hannover technological fair (Hannover Messe). In 2012, a working group was created by the German Academy of Science and Engineering to carry out a report of recommendations for the implementation of Industry 4.0 with the German government. This group, chaired by Henning Kagermann and Siegfried Dais, presented in 2013 its final set of recommendations - the “Recommendations for implementing the strategic initiative INDUSTRIE 4.0”, which has been held until today as a great theoretical precursor to the fourth industrial revolution.

With the beginning of the use of the Internet of Things (in English Internet of Things - IoT) in the manufacturing environment, it is possible to predict a short and medium term future where, according to Kagermann [2], companies will establish global networks that will incorporate their machines, storage systems and facilities in the form of cyber-physical systems (CPS). In the manufacturing environment, these CPS comprise intelligent machines, capable of exchanging information autonomously, triggering actions and controlling each other independently. This facilitates fundamental improvements in the industrial processes involved in manufacturing, engineering, material use and supply chain and product lifecycle management. Smart factories employ a completely new approach to production.

1.2. Architecture

The terms corporate architecture or enterprise architecture define the set of methods and models used to represent an organizational structure, business processes and infrastructure. An architecture is the fundamental structure of a system, shaped in its components and mutual relations and with the environment, in addition to the guiding principles of its design and evolution. An architecture aims to have a broad view of the whole of a company [3]. The modeling of an architecture should allow to establish a relationship between the strategic layers of business, application and technologies [4]. The growing technological evolution coupled with the demand of the current market makes architectures increasingly complex and their modeling requires tools with the capacity to efficiently reproduce an organizational structural model.

A well-established architectural model also allows support in decision-making in line with the business strategy. The overall view of the plant makes it possible to more clearly predict the impacts of planned changes to be made to the system. Within this context, the biggest challenge of corporate architectures is to be able to align its business strategy to execution, making the planned strategy a reality within the company. A program for modeling and maintaining an architecture should understand the company as a whole, from the people, processes, information and available technologies. Even consider beyond the relations between them, also with the external environment. According to Zaidan [5], modeling allows a holistic view of the business environment, supporting governance and assisting decisions through the view of the current state of the business process.

Architectural modeling to address automation systems was implemented a long time ago using a hierarchical model with well-defined responsibilities, from sensors and actuators, to programmable-logic controllers (PLC), to Supervisory Control and Data Acquisition Systems (SCADA), to Manufacturing Execution Systems (MES), Enterprise Resource Planning Systems (ERP). This model is based on a commitment to cost, performance and integration between systems, respecting the hierarchy defined for the existing business processes.

Emerging technologies are changing the way production systems are structured and operated, new concepts are inserted in solutions such as IoT, cloud computing, Big Data, analysis, additive manufacturing, collaborative robotics, mobile technologies, among others. System integrators are struggling to incorporate these technologies into existing systems, which sometimes have an impact on business models. This poses new challenges for automation systems

2. Method

This paper uses the ProKnow-C method for conducting the systematic literature review [16]. This method (Figure 1) starts with the definition of the search axes (themes that determines the search), followed by the stipulation of the search expression. Subsequently, reference databases on which to search are selected.

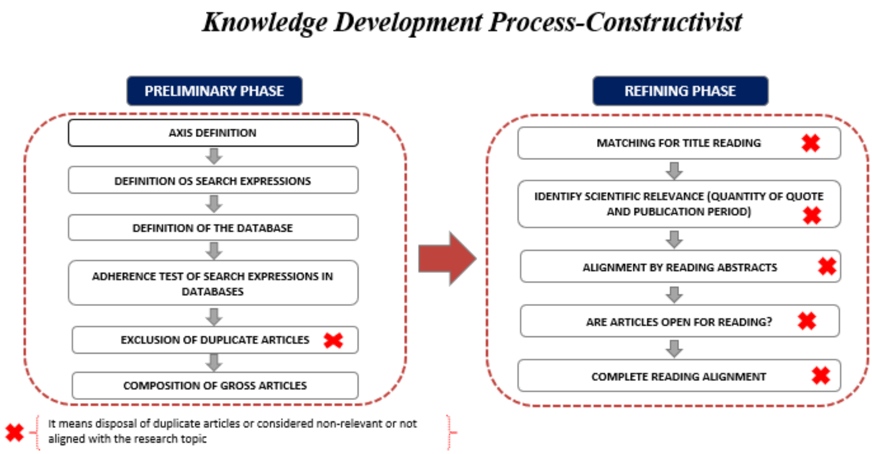

Figure 1. Knowledge Development Process-Constructivist.

To check if the selected search expression is adequate or if there are other terms that better represent the research theme, it is suggested to read three articles obtained in this preliminary search. If these five articles are considered inappropriate, it will be necessary to change the search term and reinsert it in the databases.

After the search expression adherence test, it is necessary to exclude duplicate articles (usually found in different search databases). Then, the titles of the articles should be read with the ones considered not aligned with the theme discarded (do not specifically address the research theme).

The next step is to verify the scientific relevance of the selected articles, examining the number of citations of the articles and the year of the article (written in the last 5 years).

Then, the abstracts of the articles should be read with the ones considered not aligned with the theme discarded (articles not specifically addressing the research topic), followed by the evaluation of the availability of the articles.

Next, the full articles must be read with the exclusion of those considered not aligned with the theme (considered to not specifically address the research theme), hence, builgind the final bibliographic portfolio of the research theme.

Based on the composition of the bibliographic portfolio, the analysis must be performed by verifying the evolution of the number of articles over the years, the main vehicles of publication, authors and references in addition to the network of keywords and the author's citation matrix.

3. Results

This section shows the positioning of the bibliographic portfolio followed by its analysis and, finally, the proposal of the research agenda.

3.1. Composition of Bibliographic Portfolio

Axes A and B (research themes) used consisted of "Industry 4.0" and "architecture model", respectively. Inserted in each axis, the following search expression was chosen, as shown in Figure 2.

Axis A: Architecture	Boolean operator	Axis B: Industry 4.0
("model architecture" OR "reference architecture" OR "reference architecture i4.0")	AND	("industry 4.0" OR 4th industrial revolution" OR "smart manufacturing"OR "internet of thing" OR "ĩndustrial of things")

Figure 2. Axis A and B with their respective keywords.

In addition, it was decided to restrict the search for articles published in journals and conferences, written in English and published online until the end of July 2019, considering only Scopus as the database for the composition of the bibliographic portfolio. With the insertion of the search expression in their respective databases, the preliminary results showed 81 articles.

In the next step, to check if the selected research terms are appropriate or if there are other terms that better represent the research topic, the recommendation of reading three articles was followed, as shown in Table 1.

Table 1. Adherence search expression test.

	Articles description
1	Gabriel, M., & Pessl, E. (2016). Industry 4.0 and sustainability impacts: critical discussion of sustainability aspects with a special focus on future of work and ecological consequences. Annals of the Faculty of Engineering Hunedoara, 14(2), 131. Keywords: Industry 4.0, small and medium-sized enterprises, sustainability impacts
2	Stock, T., & Seliger, G. (2016). Opportunities of sustainable manufacturing in industry 4.0. *Procedia Cirp*, *40*, 536-541. Keywords: Sustainable development, Factory, Industry 4.0.
3	Kiel, D., Müller, J. M., Arnold, C., & Voigt, K. I. (2017). Sustainable Industrial Value Creation: Benefits and Challenges of Industry 4.0. International Journal of Innovation Management, 21(08), 1740015. Keywords: Industrial Internet of Things; Industry 4.0; Triple Bottom Line; sustainability; expert interviews; multiple case study; qualitative study; manufacturing companies; German industry sectors.

Positive adherence by research themes can be observed, resulting in articles dealing with two research themes (industry 4.0 and architecture model) simultaneously, in addition to keywords similar to the search expressions.

Then, the refinement phase began, reading the titles of the 81 articles and discarding those considered not aligned with the theme (they do not specifically address the two themes), resulting in 75 articles.

Of these 75 articles, their scientific relevance was inspected, examining the year of publication and the number of citations. It can be noted that the articles were written recently, in the last 5 years, with great growth in the year 2017.

However, a small number of citations (SCOPUS was used) can be perceived when verifying scientific relevance, only two articles exceeding 100 citations. This can be explained by the agglomeration of publications in the these two years (2017-2018), which causes a low level of exposure for the scientific community. In view of this particular fact, no article was rejected and all 100 were considered scientifically relevant.

3.2. Architecture References

Considering that an rchitecture is a model of representation of a structure capable of representing the correlation of several systems [6], after reading the 75 selected articles by applying the ProKnow-C method, six architectures were identified. These architectures are the ones that could be used to develop an intelligent manufacturing solution and promote systematic standardization within Industry 4.0/smart manufacturing:

- Reference Architecture Model Industrie 4.0 (RAMI 4.0) [7]
- The Industrial Internet Reference Architecture (IIRA) [8]
- IBM Industry 4.0 Architecture (IBM)[9]
- Smart Manufacturing Ecosystem (SME)[10]
- Intelligent Manufacturing System Architecture (IMSA)[11]
- Industrial Value Chain Reference Architecture (IVRA) [12]

A summary of these architectures is presented next.

3.2.1. Reference Architecture Model Industrie 4.0 (RAMI 4.0)

The three-dimensional relationship guided by the RAMI 4.0 model makes a relationship between hierarchies, functions, and product lifecycle (Figure 3). There are 6 layers of integration responsible for making this relationship between all components of the architecture:

- **Business layer:** describes the company's organizational culture with business models, financial control and the legal sector.
- **Functional layer:** describes the technical and logical functions for the functions to be followed.
- **Information layer:** describes all information contained, whether it is real-time information, such as production data, or as information about rules or internal rules of the line.
- **Communications layer:** describes the data standards to be followed for industry 4.0 standardization.
- **Integration layer:** describes the acquisition and digitization of information, that is, the transformation of data from nature to measurable physical quantities through the digitization of information.
- **Asset layer:** represents the existing physical elements, such as equipment or product of the line, something that serves as an information base for other elements or functions.

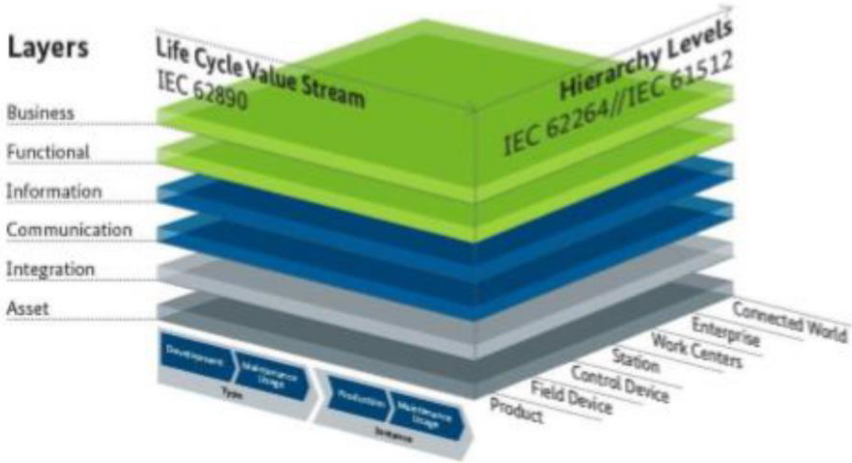

Figure 3. Idea of RAMI 4.0 [7].

3.2.2. The Industrial Internet Reference Architecture (IIRA)

The Industrial Internet Reference Architecture (IIRA) provides a five-layer description of the functions in an industrial system, their interrelation, structure, and interactions:

- **Business layer:** functions that allow operation in any industrial system.
- **Application layer:** functions that allow the management, monitoring and optimization of control systems through application logic.
- **Information layer:** functions that support the provision, transformation, modeling and implementation of data.
- **Operations layer:** functions that are responsible for provisioning, managing, monitoring components throughout their life cycle.
- **Control layer:** functions that enable the control of an industrial system.

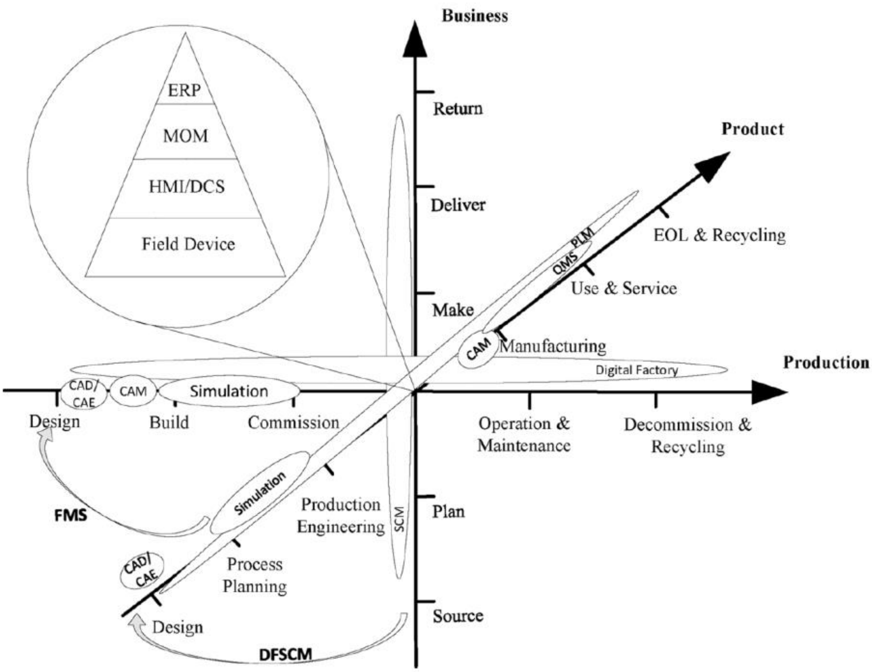

Figure 4. Idea of IIRA 4.0 [14].

3.2.3. IBM industry 4.0 architecture

The IBM industry 4.0 architecture proposes a solution based on three levels:

- **Edge level:** is widely considered a trade-off and balance between enterprise constraints, management and operations considerations, latency and performance requirements, and data privacy constraints.
- **Plant, factory or shop floor level:** the practice is to implement in each plant a service bus, often called a plant service bus (PSB), to manage local activities and connectivity with the physical environment: PLC, SCADA, OPC.
- **Enterprise or back-end level:** at the enterprise level, enterprise- or industry-specific applications are deployed for various needs: asset management,

mainterance management, consolidated data historian, ERP, optimization production scheduling, PLM, and supply chain management.

3.2.4. Smart Manufacturing Ecosystem (SME)

The Smart Manufacturing Ecosystem (SME), related to smart manufacturing, is organized along four dimensions.

- **Product lifecycle: t**he Lifeclye is from design, process planning, production engineering, manufacturing, use & service, to EOL & recycling.
- **Production lifecycle:** the lifecycle is from design, build, commission, operation & maintenance, to decommission & recycling.
- **Business**: The supply chain cycle is from source, plan , make, deliver and return.
- **Manufacturing pyramid**: this dimension is based on the IEC/ISO 62264 model.

3.2.5. Intelligent Manufacturing System Architecture (IMSA)

Intelligent manufacturing is considered to be the expression for the Chinese Industry 4.0 [13]. Intelligent Manufacturing Systems Architecture (IMSA) observes Smart Manufacturing units from three-dimension:

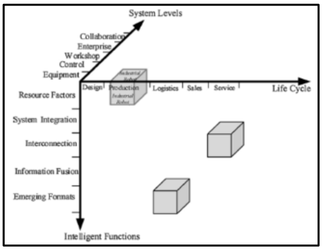

Figure 5. Idea of IMSA[14].

Intelligent functions: Collaboration, Enterprise, Workshop, Control and Equipament.
Lifecycle: Design, Production, Logistics and Service;
System levels: Resource Factors, System Integration, Interconnection, Information Fusion and Emerging Formats.

3.2.6. Industrial Value Chain Reference Architecture

Industrial Value Chain Reference Architecture (IVRA) observes Smart Manufacturing units from 3 views:

Asset view: The view shows assets valuable to manufacturing enterprises. Four classes of assets (personnel, process, product and plant) are distinguished.
Activity view: The activity view is composed of the cycle of Plan, Do, Check and Action, which is the core methodology of total quality management and business process continuous improvement.
Management view: The management view shows targets of management. Quality, cost, delivery accuracy, and environment are included.

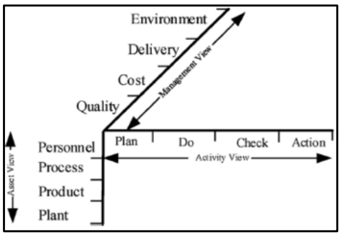

Figure 6. Idea of IVRA[14].

3.2.7. Summaries on Architectural models

Summarizing the works found above on various architectural models, we can obtain the result as shown in Table 2. This table is divided into three dimensions with its subdivisions. Each dimension of the table represents a perspective that needs to be considered when analyzing an architecture (domain, technology and information).

The information perspective is related to development in different layers and directions. Information systems are strongly linked to the design process, cloud databases and networked technologies. The technology perspective supports intelligent manufacturing, such as: new equipment, factory techniques, energies and materials. The domain perspective is related to management processes, product lifecycle, production lifecycle and supply chain.

Table 2. Summaries on architectural models.

DIMENSION	SUB-DIMENSIONS	RAMI 4.0	IIR A	IB M	SM E	IMS A	IVR A
DOMAIN	HIERARCHY LEVELS	X	X	X	X	X	X
	PRODUCT LIFECYCLE	X	X	X	X	X	X
	BUSINESS LIFECYCLE	X	X	X	X	X	X
	PRODUCTION LIFECYCLE	X	X	X	X	X	X
	MANUFACTURING MODE DEVELOPMENT	X	-		-	-	-
TECHNOLOGY	NEW EQUIPMENT	-	-	X	-	X	X
	NEW MANUFACTURING PROCESS TECHNIQUES	X	-	-	-	X	X
	NEW ENERGY	X	-	-	-	-	X
	NEW MATERIALS	-	-	-	-	-	X
INFORMATION	FUNCTION LAYERS	X	-	X	X	X	-
	COMMUNICATION TECHNOLOGY DEVELOPMENT	X	X	X	-	X	X
	NETWORK TECHNIQUE DEVELOPMENT	X	X	X	-	X	X
	DATA STORAGE TECHNOLOGY DEVELOPMENT	-	X	-	-	-	-
	DATABASE TECHNOLOGY DEVELOPMENT	X	-	-	-	X	-
	IT INFRASTRUCTURE DEVELOPMENT	X	X	-	-	X	X
	SIMULATION TECHNOLOGY DEVELOPMENT	X	-	-	X	-	-

4. Conclusion

This work presents a systematic review of the literature, with an overview of captured architectural models for Industry 4.0 and a brief comparison of them.

When considering the results of the present study, several limitations should be noted. First, the articles were collected in only one database (Scopus). Second, because the search criteria restricted the language of the article collected to English, existing searches that have been published in other languages have been excluded. Third, only articles from magazines and conferences were considered. Therefore, this review could be more comprehensive if more databases, languages and types of vehicles were also taken into account. However, as a systematic review of the literature, appropriate restrictions must be specified for the review to be viable.

Intelligent manufacturing is related to information and communication technology, industrial technology and management technology. The intelligent manufacturing system is a complex, large-scale system that must encompass these technologies. In this sense, standardization is a powerful tool to drive the development and implementation of smart manufacturing technologies. Currently, existing standards are organized into related architectures. The article presents the main existing architectural models. Among the models, the RAMI model stands out, which is presented as a relevant reference, with a focus on guiding the development of a reference models, from a more technical point of view, through different performance layers of the aspects facing the shop floor to strategic decisions by business areas. Future research can be conducted to identify which existing architecture models address the views of Industry 4.0 using multicriteria methods.

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