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Chapter 4: Referential Architectures of Cyber-Physical Systems (CPS) for INDUSTRY 4.0

Chapter 4: Referential Architectures of Cyber-Physical Systems (CPS) for INDUSTRY 4.0

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Abstract

Nowadays, we observe an increasingly rapid growth of connected objects and data produced at all levels of modern society and particularly in the industrial world. A new industrial revolution has therefore appeared, under the name of Industry 4.0, aiming in particular at designing and implementing so-called cyber-physical systems allowing to face new important challenges linked to an intelligent use of ICT technologies in order to be able to propose products and services adapted to the society of tomorrow. This chapter introduces several referential architectures for Industry 4.0 and proposes a 5C layered architecture enhancement intended to facilitate designing, developing and managing Cyber Physical Systems. The two lowest layers are intended to cope with the integrability (connectivity) and interoperability (communication) challenges of the heterogeneous actors involved in CPS (people, things, data, services, etc.). The three highest layers are intended to incrementally integrate monitoring, analysis, planning and management capabilities required to allow coordination of CPS as well as cooperation and collaboration of Cyber-Physical Systems of Systems (CPSoS).

4.1 Introduction

Industry has not stopped evolving over the years. At the end of the 18th century, we saw the emergence of the first industrial revolution characterized by the invention of steam engines. The second industrial revolution appeared a hundred years later and was born from the intensive use of resources such as electricity, oil or chemical products in order to produce in mass. We can notice that these two revolutions were marked by major scientific advances

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linked to energy sources, contrary to the third industrial revolution which appeared in the 1970s with the appearance of the first programmable controllers allowing the advent of digital programming of automation systems linked to information technologies.

Currently, a new industrial revolution is emerging, Industry 4.0, which is mainly related to the strong scientific advances concerning ICT technologies. A major challenge of today is to obtain a total connection between all the actors of one or several environments (humans, things, systems, connected data). We can decompose this problematic in two approaches to be solved, namely: how to design efficient models in order to manage the heterogeneous and more and more important quantities of data and how to use in an optimal way the collected information in order to produce knowledge and to obtain services adapted to the constraints of the Industry 4.0 era.

This industrial revolution, which can be described as digital, has given rise to particularly complex problems to be solved because several recent cutting-edge technologies must work together, such as the Internet of Things, big data, artificial intelligence and cloud computing. For this, a methodology and a reference architecture are needed to ensure the transition process from a standard organization to a connected or digital organization.

Many government agencies and private organizations, including mainly the world's leading powers, have already launched initiatives to define a reference architecture to ensure the transition process to a connected organization adapted to the needs of emerging markets.

These initiatives and their reference architectures have different foundations and orientations which, despite fulfilling their role as a guideline and roadmap, still need to be enhanced to facilitate designing, developing and managing Cyber Physical Systems. This chapter aims at identifying the key and common aspects of these different abstract reference architectures in order to propose a 5C layered architecture enhancement intended to facilitate designing, developing and managing Cyber Physical Systems. The two lowest layers are intended to

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cope with the integrability (connectivity) and interoperability (communication) challenges of the heterogeneous actors involved in CPS (people, things, data, services, etc.). The three highest layers are intended to incrementally integrate monitoring, analysis, planning and management capabilities required to allow coordination of CPS as well as cooperation and collaboration of Cyber-Physical Systems of Systems (CPSoS). Therefore, this 5C layered architecture is intended to address the following challenges for Industry 4.0 CPS: process management for integration, interoperability, development and operation of intelligent products and services.

This chapter is organized as follows: the first section describes the context and explicitly describes the main challenges of the fourth industrial revolution. The second section presents the main existing referential architectures. The third section presents a proposed 5C layered architecture for the design, implementation and management of Industry 4.0 systems. Finally, the conclusions and perspectives of this work will be presented.

4.2 Background and challenges statement

In their dynamic of continuous improvement and digitalization, organizations are seeking to integrate advanced and innovative technologies to ensure their transition to Industry 4.0. Indeed, the emergence of Industry 4.0 brings a technological and philosophical revolution in companies, forcing them to question their business models. The term "Industry 4.0" encompasses a set of technologies and concepts related to the re-organization of the value chain (Hermann et al., 2015).

Today, we are living this new industrial revolution, which is directly related to the accelerated advances enabled and promoted by information and communication technologies (ICT). It relies on the communication of real-time information to monitor and act on physical systems, thus exploiting a new paradigm: the cyber-physical systems (CPS). Different

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systems communicate and cooperate with each other, but also with humans, to decentralize decision-making. Industry 4.0 focuses on connectivity, thus fostering the development of new processes to integrally manage products manufacturing and services provision. Its deployment requires the integration of different digital technology know-how (Danjou et al., 2017).

The current digital revolution in our society, represented by the Internet of Things (IoT), Social Networks, Cloud Computing, Big Data and Artificial Intelligence (AI), offers unlimited opportunities for the development of the companies of the future. Today we speak of digital organizations resulting from the integration of people, objects, data, processes and services, i.e. the Internet of Everything (IoE) (Bradley et al., 2013; Lee et al., 2017). However, the transition from a traditional organization to an "intelligent" and "digitized" organization is a complex process to implement.

In order to help organizations in their industrial transition and overcome these challenges, this chapter breaks down this huge challenge that is Industry 4.0 into two distinct areas:

- Connection, acquisition, processing and storage of heterogeneous data collected,
- Implementing efficient decision models and defining strategies to have significant flexibility and responsiveness to customers.

4.2.1 Data management for a fully connected world

In recent years, it is easy to see that the growth of connected objects is increasingly rapid at all levels of modern society and especially in the industrial world. The same goes for the data produced, which is increasing exponentially year after year. We can clearly say today that we are heading towards a Fully Connected World (FCW).

Initially, it was the things that began to get connected giving birth to the concept of Internet of Things (IoT) and the enormous opportunities envisioned (Ashton, 2009; Gershenfeld et al.,

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2004; Atzori et al., 2010). In the same vein, the idea of connecting machines and allowing communication between them gave rise to the concept of machine-to-machine (M2M) (Wu et al., 2011). In order to foster interoperability and narrow the scope of the Internet, the concept of Web of Things (WoT) was proposed to encompass open protocols and facilitate access to the connected things (Bradley et al., 2013).

The approach of interconnecting things or machines was opportunely extended by Cisco in 2013 to identify new market and innovations opportunities leading to the fully connected world: The Internet of Everything (IoE) or the intelligent connection of people, things, data and process (Guinard et al., 2009). This vision has been naturally associated with other definitions such as the Internet of Data (IoD), Internet of Services (IoS) and Internet of People (IoP) (Weber et al., 2010; Schroth et al., 2007; Conti et al., 2017).

In the FCW paradigm, the amount of collectable data grows exponentially and the need for its processing, very often in real time, is essential to produce meaningful information and in particular to create new knowledge.

Existing solutions in the area of Business Intelligence (BI), Analytics or Artificial Intelligence (AI) have been successfully applied for years on the basis of data from traditional information systems in order to support strategic decision making (Bordeleau et al., 2018). However, the quantity, heterogeneity and frequency of the potentially collectable data under the FCW paradigm reveal new challenges that have given rise to important innovations in the area of Big Data (Lee et al., 2014; Wang et al., 2016).

4.2.2 Acting smartly upon a fully connected world

Many works have been interested in proposing Data Science methodologies and applications to meet the challenges of implementation and managing CPS for Industry 4.0. The development of Cyber-physical systems and the Internet of Things (IoT) is accelerating,

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leading to the transformation of our economy and society. New challenges are emerging for Data Scientists but also for business owners in particular to cope with the needs of providing real-time predictive and prescriptive dashboards based on past, current and future data in continuous evolution. For this, a well-adapted design and development methodology and corresponding reference architecture are needed in order to provide an efficient ecosystem promoting innovation and creativity.

However, there are cases in which the predictions or prescriptions proposed by decision models are difficult to interpret and rather vague, which makes users skeptical about their actual use. That is why we need models that will increase user confidence in particular by developing the interpretability of machine learning systems recommendations.

The design and implementation of smart cyber-physical systems following an appropriate methodology and based on a concrete architecture that meet the challenges of integrating IoE actors and their intelligent coordination (agile, adaptable, reconfigurable and flexible) is needed. Indeed, CPS have become one of the pillars of the factory of the future. They should autonomously provide information about themselves and exchange information with other CPS that are part of the industrial networks. They should be able to be adaptive to respond to multi-domain challenges involving different paradigms. We are talking about cyber-physical systems of systems (CPSoS).

This concept, which is strongly emerging, is a priority research area today because it allows us to respond to several societal challenges from different disciplines such as systems engineering or computer science (Gharib et al., 2018).

One of the main challenges for the integration of CPSoS operating as a fully integrated system is the autonomy of its components. They will surely become ubiquitous in our society, whether in companies, homes or cities. In order to achieve this scenario, technological advances are necessary in the modeling, analysis but also in the control of CPS failures.

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Today, the focus is on the management of complex, heterogeneous and distributed networks comprising a multitude of compute nodes. Numerous distributed computing resources (embedded systems, smartphones, high performance computing) will allow the emergence of new services thanks to the interaction of functional components.

This design method should be easily adaptable to new contexts and respond effectively to new needs. These new requirements will include human interaction, scalability, functional verification and safety.

4.3 Architectures of reference

In order to guide organizations in their transition to the 4th industrial revolution and to create an environment conducive to innovation and to the creation of CPS adapted to efficiently meet the new needs, several initiatives have been launched around the world and several architectures have been proposed.

4.3.1 Industry 4.0 initiatives

The most significant initiatives have been accompanied by government agencies and private organizations from countries in the most developed economies (Wang et al., 2017; Zhong et al. 2017). Reference architectures provide a framework for developing solutions for Industry 4.0 in a structured way that allows all participants to be involved in a uniform manner. In this sense, standards can be identified and optimized. Among these architectures, we will find well known ones like the Reference Architectural Model Industrie 4.0 (RAMI4.0) and the Industrial Internet Reference Architecture (IIRA).

RAMI4.0 is a reference architecture that originated in Germany to provide a framework for determining and implementing the most efficient technologies and methods to revolutionize the industrial world. It is currently one of the most popular and impactful reference

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architectures in the world.

IIRA, on the other hand, was created in the USA and can be compared to RAMI4.0 (Lin et al., 2017). In spite of some similarities, these two architectures differ on many points that we will discuss in this work in order to show the advantages and disadvantages of each. These differences are mainly explained by the fact that these initiatives have been carried out separately.

Other different but interesting work has been carried out with so-called cognitive architectures because they allow the integration of self-management capabilities. Among these, we find the Adaptive Control of Thought - Rational (ACT-R) architecture or the Soar architecture.

Other notable initiatives are the Made in China 2025 project (Ling, 2018) and the Japanese Industrial Value Chain (IVI) project (Zhong et al., 2017) which advocate industrial and technological collaboration.

This work will focus mainly on the reference architectures RAMI4.0 and IIRA, which are currently the architectures with the most potential.

4.3.2 Industry 4.0 reference architectures

As mentioned above, the RAMI 4.0 and IIRA reference architectures aim to facilitate the Industry 4.0 knowledge sharing paradigm, guide organizational transitions, and specifically advise on leveraging ICT advances. Both initiatives seek to build a more efficient industrial world particularly through complex, connected and intelligent systems. A notable difference is that RAMI 4.0 extends this vision to the entire value chain and product life cycle, while IIRA maintains a more concrete vision of the ICT world.

Reference Architectural Model Industrie 4.0 (RAMI4.0)

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The RAMI4.0 architecture is based on three dimensions, [as we can see in Figure 4.1 below](#), namely: the layers (properties and system structures), the hierarchy levels (from the product to the connected world) and the life cycle and value stream (product lifecycle).

The first vertical axis proposes 6 layers (asset, integration, communication, information, functional and business) allowing to break down the properties of a machine on different levels. Thanks to this, even the most complex systems can be divided and managed more easily.

Regarding the second right horizontal axis, the hierarchy levels, from IEC 62264, represents the different functionalities of organizations. This dimension characterizes the Industry 4.0 revolution with the introduction of "Products" as well as the "Connected World" with the emergence of the connection of things and services (IoT).

Finally, the left horizontal third axis targets the products and facilities lifecycle, based on IEC 62890. We can identify 2 phases: types and instances. The type phase is characterized by the design and prototyping of a product. When this phase is completed and the product is manufactured, the type phase becomes instance.

Industrial Internet Reference Architecture (IIRA)

The Industrial Internet Reference Architecture was introduced, in 2015, by the Industrial Internet Consortium (IIC) and updated in 2017 to become an open standards-based architecture for the Industrial internet of Things (IIoT). The architecture proposes 3 dimensions, [as we can see in Figure 4.2](#), comparable to the Reference Architectural Model Industrie 4.0 (RAMI4.0), namely: the Viewpoints (Business, Usage, Functional and Implementation), the Process Lifecycle (IIoT system conception, design and implementation) and the Industrial Sectors.

A major goal of IIoT is to connect larger, complex systems and implement hierarchies for

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machines. This architecture is also based on IIoT systems for the functional part with a decomposition in 5 interconnected domains, namely: control (control and actuation), operations (management and maintenance), information (data collection and analysis), application (use-case application) and business (business goals).

Made-in-China 2025

From an economic point of view, China is no longer in the market of very low-cost manufacturing because of the arrival of new competing producers such as Cambodia or Vietnam. On the other hand, China is also not at the top in terms of high-quality manufacturing. Countries such as the United States, Germany or Japan have very advanced means to produce efficiently and qualitatively proposing products always more innovative while respecting very strict quality charters.

In order to become more competitive, China has decided to launch the "Made-in-China 2025" project. This project has precise and well-defined objectives. Several key axes emerge from it, such as giving priority to quality over quantity, which has long been the model chosen until now, strengthening Chinese industries by connecting all the manufacturing chains, choosing a more eco-responsible production or even the perpetuation of human expertise.

Like the Industry 4.0 plan, the Made-in-China 2025 plan proposes the use of IoT to optimize manufacturing processes and make them intelligent, whether inside or outside the factory, to ensure responsive exchanges and optimal product traceability. In summary, the paradigm proposed by Made in China 2025, is mainly translated into the Intelligent Manufacturing System Architecture (IMSA), based on the wide adoption of ICT for digital manufacturing.

This plan, like the Industry 4.0 plan, has nevertheless some points to be wary of, such as the important technological gap that can be created between the industrial world and the societal world, for example, or the strategies and limits to be established during inter-company or

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even inter-country collaboration (Lin et al., 2017).

Industrial Value Chain Initiative (IVI)

Amidst the trends related to IoT technologies that are intensifying worldwide, the Industrial Value Chain Initiative (IVI) supports the transformation and improvement of Japan's manufacturing industry. The IVI is a forum that provides a place where people from different companies can be connected. In this approach, humans and factories play an important role. During the various consultations, several topics are discussed and considered in order to meet multiple needs such as predictive maintenance via IoT or the digitalization of expert knowledge and techniques. Some ideas are evaluated and the results are then disseminated in symposiums and publications, allowing other manufacturers to refer to them to address similar challenges.

This approach is based on two axes, namely smart manufacturing and the freely defined standard. The first axis seeks to optimize production lines and create intelligent value chains through automation and human expertise. As for the second axis, it proposes the use of an adaptable model rather than a rigid model. So by using connectivity based on the loosely defined standard, IVI seeks to increase the value of each company through cyber-physical production systems (IVI, 2016).

While European and North American industries advocate top-down smart manufacturing, Japanese industry, which is good at shop floor and worker-centered Kaizen (improvement) activities, offers a reference architecture containing a Japanese manufacturing mindset via the IVI.

Other architectures integrating self-management capabilities.

- a) **Adaptive Control of Thought - Rational (ACT-R)**

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ACT-R is a cognitive architecture and more precisely a theory based on the understanding of human cognition. This architecture allows, in particular, the creation of simulation models of cognition (learning and memory) (Ritter, 2019). The objective is to understand how humans organize information and knowledge and how cognitive behaviors are produced. In this sense, ACT-R allows the acquisition of detailed information about how humans perceive and interact with the world.

According to ACT-R, human Knowledge is the result of the interaction between declarative and procedural knowledge.

Declarative knowledge is represented in the form of vectors called "chunks" accessible via buffers.

Procedural knowledge is represented in the form of formal notations specifying the flow of information to the cortex, called "productions".

This architecture allows, therefore, an efficient access to information, but the amount of data is complex to manage.

b) Soar

Soar is a cognitive architecture implemented in 1983 and which has since evolved through several versions with today's version 9.

This architecture is used in several domains such as the representation and use of knowledge, the interaction with the external world, but especially the development of computational systems necessary for intelligent agents. These agents are able to execute a multitude of tasks and learn different types of knowledge in order to perform cognitive actions found in humans (decision making, natural language understanding).

Soar is based on the interaction between procedural memory (knowledge about how to do things) and working memory (representation of the current state).

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The procedural memory is represented by if-then rules that constantly try to match the content of the working memory and the working memory is represented by a symbolic graph structure. When the values of the two memories match, it is called a production system (Soar, 2022).

4.4 5C layered referential architecture for CPS

In order to facilitate and assist in the design, implementation and management of cyber-physical systems for Industry 4.0, a referential architecture in 5C layers will be presented in this section. This referential architecture is intended to build and coordinate CPS and to allow cooperation and collaboration of CPSoS. This architecture is well suited for CPS involved in Industry 4.0 manufacturing processes, as well as for the elaboration of smart products and the provision of smart services.

The standard reference architectures described above provide a systemic vision that aims to build complex, connected, intelligent systems. Although the IIRA architecture favors the term Industrial Internet of Things (IIoT), one could generalize that both reference architectures are oriented towards the development of intelligent systems that could be represented by cyber-physical systems. Indeed, Industry 4.0 systems are characterized by the fact that they are composed of physical and computational entities that need to interact accordingly in order to achieve specific goals, such as producing smart products or providing smart services. Moreover, these smart products could also be built from instances of CPS.

In order to ensure that the goal of common understanding and integration of new technologies within the framework of Industry 4.0 can be guaranteed in a tangible way, it is necessary to extract key elements from these reference architectures, in particular to guide the design and development of cyber-physical systems.

This proposal promotes a generic and concrete architectural framework, based on a 5C

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layered architecture and resulting from an enhancement of the reference architectures previously presented.

4.4.1 5C Layers

The 5C Layered architecture follows an incremental approach that allows the assembly of components of a CPS and also goes as far as its composition to create systems of systems.

The two lowest layers (C1..C2) are intended to cope with the integrability (connectivity) and interoperability (communication) challenges of the heterogeneous actors involved in CPS (people, things, data, services, etc.). The three highest layers (C3..C5) are intended to incrementally integrate monitoring, analysis, planning and management capabilities required to allow coordination of CPS as well as cooperation and collaboration of Cyber-Physical Systems of Systems (CPSoS).

The [Table 4.1](#) presents each layer and describe the architectural functionalities offered to the involved entities.

Table 4.1: Architecture layers and functionalities

Layer	Description	Architectural functionality
C1: Connection	entities share a common medium or channel	Network connectivity
	two or more entities are able to understand each other by exchanging messages via a common medium or channel	Integrability
C2: Communication		Interoperability
		Interaction modes
		End devices and access networks (Things and People) Internet Data centers (Data, People and Services) Object/Procedure oriented (ORB / RPC) Message/Event oriented (MOM / EDA) Service/Micro-service oriented (SOA / MSA) Syntactic Semantic Cross-domains and Open standards Synchronous/Asynchronous IN-only, IN-OUT, OUT-IN, OUT-only Request/Reply Publish/Subscribe Push/Pull

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C3: Coordination	two or more entities working together following the orders or the instructions of a coordinator	Intra-system orchestration (CPS)
C4: Cooperation	two or more entities work together to achieve individual goals	Inter-systems orchestration (CPSoS)
C5: Collaboration	two or more entities work together to achieve a common global goal	Inter-systems choreography (CPSoS)

4.4.2 Autonomic Management dimension

In addition to the 5 levels previously presented representing a structural dimension for the design of CPS and CPSoS, our architecture must also integrate a behavioral dimension allowing the intelligent management of the structural elements involved.

This behavioral dimension must offer a generic and scalable approach, allowing to offer self-adaptation capabilities to the context in order to enable the achievement of the goals established for the CPS.

We believe that the architecture proposed by autonomic computing (AC) offers the framework required to integrate this behavioral dimension for self-management.

The AC was proposed by IBM about two decades ago in order to respond to the increasing complexity of the manual management of IT-based systems (Horn, 2001; Kephart et al., 2003; IBM, 2006). This architecture offers several structural and behavioral

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recommendations to implement self-management capabilities and thus build an autonomic system.

The term autonomous has a Greek origin and its meaning is "self-managed". The AC is an example of biomimicry as it is inspired by the human autonomic nervous system, based on the control of the body's vital functions without explicit conscious effort. In the case of software systems, the AC approach aims at implementing self-management functions avoiding user intervention.

The self-management functions of an autonomous system aim to implement adaptive actions derived from changes or events observed in the environment and intended to achieve a desired goal or state or to continue to provide the expected service. Adaptive actions are implemented by adaptive algorithms operating within a closed-loop control system. These algorithms can be generically described as a process that includes monitoring, analysis, planning and execution (MAPE) activities that share a common knowledge base.

- **Monitoring:** observes the system by collecting or detecting relevant data or events.
- **Analysis:** compares the observed data with the expected values to detect needs for change in order to achieve the planned objectives.
- **Planning:** selects or develops strategies to achieve the planned objectives.
- **Execution:** executes adaptation or adjustment actions on the controlled system.

Since IBM's autonomic computing initiative in 2001, a significant number of industrial organizations have actively collaborated in the design and development of AC systems. Examples of these efforts are: Microsoft's Dynamic Systems Initiative (DSI), Hewlett Packard's Adaptive Enterprise, Sun's Sun Grid Engine (SGE), Dell's Dynamic Computing Initiative, etc.

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With regard to our 5-level structure, the autonomic behavior would develop progressively, starting from the lowest levels thanks to the implementation of the required functionalities at the level of connection and communication to retrieve observations and execute adaptation actions on the CPS actors. At the coordination level, the autonomic MAPE process will allow to self-manage the actors involved in order to achieve the objectives set for the CPS. At the cooperation and collaboration levels, the CPS will function as actors that can be monitored and who can carry out adaptation actions in order to achieve the individual or shared objectives of the CPSoS.

Having now the structural and behavioral dimensions of our architecture in place, a suitable methodology is still required to guide the process of building CPS based on our reference architecture. The following section will introduce a well-suited system engineering methodology that could be followed to build CPS based on the Autonomic 5C layered architecture.

4.4.3 System engineering methodology

In order to help innovation and development project managers in their transition to a more connected industry adapted to tomorrow's needs, we propose a methodological approach to determine and define precisely the different phases allowing to design and integrate complex systems related to Industry 4.0.

In the area of software engineering and systems engineering, several methodologies and modeling frameworks have been proposed for the development of complex systems. For reasons of limited space, this section will not go into details about traditional methodologies, such as (Rational/Agile) Unified Process based on the Unified Modeling Language (UML) or Systems engineering methodologies based on SysML.

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A recent methodology successfully used at the industrial level for system engineering and based on this standard is the ARCADIA methodology. This methodology is an example of an MBSC methodology that also includes a language (Roques, 2016). We cannot directly compare UML or SysML with ARCADIA because ARCADIA is both a language and a method. When we make the comparison, it is only with the modeling language that is inside Arcadia.

ARCADIA is an acronym that stands for ARChitecture Analysis and Design Integrated Approach. It is a model-based engineering method for the architectural design of systems, hardware and software. It was developed between 2005 and 2010 by Thales through a process that involved many architects and many different units. Arcadia has been influenced by systems engineering and in particular the distinction between requirements and solutions (Thalès, 2021).

This method also promotes a viewpoint approach. The central viewpoint in Arcadia is a functional viewpoint. Functions are used to describe what the system needs to do, and then functions to describe what the logical or physical components do and how, what they do, will contribute to the system. In addition, other points of view such as performance or security must be satisfied and conform to the context of the specific project. This allows the same system to be seen from many different points of view depending on the system to be designed. All the architect's work, finally, will be to find the best compromise between all these points of view.

A system can be separated into two parts: what the system has to do and the solution. The fundamental distinction is between defining the problem well with the customers (end users) and then proposing a well-defined solution that meets the specification, [as we can see in the Figure 4.3.](#)

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This methodology proposes 5 incremental phases to identify the functional and non-functional requirements of the system (operational and functional analysis phases) and to design the system architecture (logical and physical architectures and EPBS). [These phases are summarized in the Table 4.2 below.](#)

Table 4.2: Arcadia methodology including needs analysis and design architecture phases

OPERATIONAL ANALYSIS	What the users of the systems need to achieve	identifying the actors that must interact with the system their activities and their interactions
ANALYSIS OF THE SYSTEM NEEDS	What the system has to provide to the users	proposes external functional analysis identify the system functions needed by the users
LOGICAL ARCHITECTURE	How the internal components of the system will work to fulfill requirements	internal functional system analysis (sub-functions) identification of the logical components (implementing internal sub-functions and assuring non-functional constraints)
PHYSICAL ARCHITECTURE	How the system (internal components) will be developed	concrete architecture of the system Integrated implementation functions based on specified logic and technological decisions

The operational analysis is the first step. It mainly allows the definition of the customer's needs and objectives but also the planned exchanges and activities. This level, in Arcadia, helps to better define the level of analysis of the system in particular thanks to the definition of IVVQ (Integration, Verification, Validation and Qualification) conditions and the management of operational constraints such as the life cycle or security. As soon as we start talking about a specific technology, it's time to move on to the physical architecture.

The second step, the system or functional analysis, now focuses on the system itself to define how it can satisfy the business needs defined in the previous step. It is usually a black box with several functions inside that will help to partially automate, probably a subset of the business needs (performance, constraints, ...). The feasibility of the customer requirements is

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also analyzed in this step, in order to identify the parts that are not feasible in terms of cost or time for example. In general, a first validation point is carried out with the customers at this stage before moving on to the modeling of the architectures.

The third step, the logical architecture, consists in opening the black box. The logical components will be defined as well as their interaction between them. It is very interesting to define a first level of architecture of internal components that are not yet linked to a specific implementation or technology. One of the main advantages is that the logical components will be very stable over time. That is, you can have three, four or five different physical architectures using different technologies but the logical architecture will remain unchanged. This is a kind of intermediate high-level view of the design. Moreover, the formalization of the different points of view will allow the impact of these constraints on the system to be measured and revised if necessary.

The physical architecture is the fourth level where the physical components, which will be needed inside your system, hardware or software, are defined. The level of detail is free depending on the need and requirements. This level of architecture is the most detailed level where the largest number of components are found, usually in an Arcadia Capella model. This step is also guided by the viewpoints with a high degree of precision in the way they are taken into account for each component.

Finally, the fifth level, the EPBS (End-Product Breakdown Structure), is no longer considered a real architecture level. Rather, it is seen as an additional viewpoint on the physical architecture. It is more about how these physical components will be distributed to internal designers or subcontractors. Therefore, at this level, no new functions are added but the physical components are grouped into two groups that will be under the responsibility of different teams (internal or external). In general, as we go down, we observe a more and more precise refinement which is the case for the first four levels. However, when moving from the

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physical architecture to the EPBS, fewer concepts are observed due to the fact that in this level, one or more physical components will be grouped together. Moreover, there is no function at this level so nothing is refined. In this sense, several documents present, today, this method with only four different levels.

In summary, there is the operational analysis and the system analysis (functional analysis) that help define what the system must do. There is the operational analysis of the customer's needs and the analysis of the system's needs. Then there are the levels for the architecture with the logical architecture, the physical architecture and the EPBS. Moreover, the method has its own language mainly due to the lack of the concept of functions with languages like UML or SysML. Arcadia can be applied top-down, bottom-up, incremental or relative in the middle so it is possible to do agile modeling.

Our methodology is based on an extension of the Arcadia methodology, in order to integrate additional viewpoints and views, capable of incorporating the structural and behavioral levels of our referential architecture for Industry 4.0 CPS.

4.5 Conclusions and perspectives

This chapter has presented the motivations for providing an adapted architecture for Industry 4.0 systems. Several well-known referential architectural and initiatives have been presented and compared. Based on this study, an enhanced referential architecture and a well-adapted methodology facilitating the design, development and management of Autonomic Cyber Physical Systems for the Industry 4.0 has been presented. This architecture follows a multi-layered approach and introduces the foundations of the structural and behavioral dimensions for the integration, interoperation, coordination, cooperation and collaboration layers of Autonomic CPS. The proposed methodology, resulting from the Arcadia methodology, is intended to design and implement the autonomic properties by incrementally including the

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required monitoring, analytics, predictive and prescriptive capabilities of self-managed CPS and CPSoS.

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Figure Legend

Figure 4.1: Reference Architectural Model Industrie 4.0 (RAMI4.0) (Based on Plattform Industrie 4.0 and ZVEI 2015)

Figure 4.2: Industrial Internet Reference Architecture (IIRA) (Based Industrial Internet Consortium 2017).

Figure 4.3: ARCADIA Methodology (Source: Capella MBSE – Arcadia 2015).