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A novel migration approach towards decentralized automation in cyber-physical production systems

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Preface

This thesis is the result of my work as research assistant at the Institute of Ergonomics, Manufacturing Systems and Automation (IAF) of the Otto-von-Guericke University Magdeburg and external PhD student at Siemens Corporate Technology in Erlangen.

I want to thank my doctoral supervisor apl. Prof. Dr.-Ing. habil. Arndt Lüder. His positive and productive support during these years helped me to find a clear vision and improve my research. And I want to thank my supervisor on the industry side, Dr.-Ing. Matthias Foehr. His numerous critical stimuli and attention to details helped me to shape this work.

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Moreover, I thank all colleagues of the chair of Factory Operations and Manufacturing Systems and of the research group Engineering Methods and Tools at Siemens Corporate Technology, especially Jan Vollmar, Dr. Michael Gepp and Jürgen Elger for their friendship, strong support and fruitful discussions.

Finally, I am very grateful to my parents, sister and my fiancé Riccardo, who always encouraged me in my ventures and supported this work.

Magdeburg, 02.10.2018 Ambra Calà

Abstract

Manufacturing industries have recognized the continuous need to change their current production systems in order to face new market requirements of shorter product lifecycle, increased product variety and shorter time-to-market. Within the context of the fourth industrial revolution, the German Industry 4.0 initiative supports the transformation towards flexible and reconfigurable Cyber-Physical Production Systems (CPPS) based on Internet of Things (IoT), Cyber-Physical Systems (CPS) and Cloud technologies.

Several technologies have been developed towards the decentralization of automation architectures and the introduction of new intelligent systems for the realization of the so called “Smart Factories”. However, these technologies have not been yet implemented in industry due to the manufacturers’ conservatism in radical changes and the lack of smooth and well-defined migration path towards CPPS. Although migration processes and strategies already exist in literature, approaches that deal with the migration of traditional production system towards the fourth industrial revolution are still missing.

This thesis proposes a novel migration approach to support manufacturers in the stepwise migration of their current infrastructures towards decentralized automation in CPPS. The aim of the stepwise approach is to identify the business opportunities related to the introduction of digitalization and robotization in manufacturing companies and prioritize those areas in which Industry 4.0 technologies would offer the most benefit.

The first part of the thesis provides some definition of the Industry 4.0 paradigm and digital technologies, investigating how the upcoming revolution will affect the tradition manufacturing. In addition, it analyzes existing migration strategies and processes in literature as well as related engineering practices, pointing out the lack of specific methodologies that can support the migration towards CPPS.

The second part of the thesis describes the so called HoMoCPPS approach, which represents a holistic migration approach towards CPPS based on a 5-phase process. The logic of the approach as well as the migration process and its embedded methods and tools are described in details. Moreover, the thesis covers the application of the migration approach in industry. The results of its implementation in a real case study are presented in the end, showing the benefit of the proposed migration approach.

Kurzfassung

Die verarbeitenden Industrien haben erkannt, dass ihre derzeitigen Produktionssysteme ständig geändert werden müssen, um den neuen Marktanforderungen nach einem kürzeren Produktlebenszyklus, einer größeren Produktvielfalt und einer kürzeren Time-to-Market gerecht zu werden. Im Rahmen der vierten industriellen Revolution unterstützt die Initiative Industrie 4.0 den Wandel zu flexiblen und rekonfigurierbaren Cyber-Physical Production Systemen (CPPS) basierend auf Internet of Things (IoT), Cyber-Physical Systems (CPS) und Cloud-Technologien.

Mehrere Technologien wurden entwickelt, um Automatisierungsarchitekturen zu dezentralisieren und neue intelligente Systeme für die Realisierung der sogenannten "Smart Factories" einzuführen. Diese Technologien wurden jedoch noch nicht in der Industrie implementiert, da die Hersteller in radikalen Veränderungen konserviert sind und ein reibungsloser und gut definierter Migrationspfad in Richtung CPPS fehlte. Obwohl Migrationsprozesse und -strategien bereits in der Literatur existieren, fehlen noch Ansätze, die sich mit der Migration des Traditionsproduktionssystems in Richtung der vierten industriellen Revolution befassen.

Diese Arbeit schlägt einen neuartigen Migrationsansatz vor, um Hersteller bei der Migration ihrer derzeitigen Infrastrukturen in Richtung einer dezentralen Automatisierung in CPPS zu unterstützen. Ziel des schrittweisen Ansatzes ist es, die unternehmensrelevante Einführung von Digitalisierung und Robotisierung in produzierenden Unternehmen zu identifizieren und diejenigen Bereiche zu priorisieren, in denen Industrie 4.0-Technologien den größten Nutzen bieten.

Der erste Teil der Arbeit liefert eine Definition des Paradigmas der Industrie 4.0 und digitaler Technologien und untersucht, wie sich die bevorstehende Revolution auf die traditionelle Fertigung auswirkt. Darüber hinaus analysiert es bestehende Migrationsstrategien und -prozesse in der Literatur sowie verwandte technische Verfahren und weist auf das Fehlen spezifischer Methoden hin, die die Migration zu CPPS unterstützen können.

Der zweite Teil der Arbeit beschreibt den so genannten HoMoCPPS-Ansatz, der einen ganzheitlichen Migrationsansatz für CPPS auf der Basis eines 5-Phasen-Prozesses darstellt. Die Logik des Ansatzes sowie der Migrationsprozess und seine eingebetteten Methoden und Werkzeuge werden detailliert beschrieben. Darüber hinaus behandelt die Arbeit die Anwendung des Migrationsansatzes in der Industrie. Die Ergebnisse seiner

Implementierung in einer realen Fallstudie werden am Ende präsentiert, was den Nutzen des vorgeschlagenen Migrationsansatzes zeigt.

Declaration of Honor

I hereby declare that I produced this thesis without prohibited external assistance and that none other than the listed references and tools have been used. I did not make use of any commercial consultant concerning graduation. A third party did not receive any nonmonetary perquisites neither directly nor indirectly for activities which are connected with the contents of the presented thesis.

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This work has not yet been submitted as a doctoral thesis in the same or a similar form in Germany or in any other country. It has not yet been published as a whole.

Magdeburg, 02.10.2018 Ambra Calà

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Abbreviations

AD	Activity Diagram
BDD	Block Definition Diagram
BPML	Business Process Modeling Language
BPMN	Business Process Modeling Notation
CAD	Computer Aided Design
CMM	Capability Maturity Model
CMMI	Capability Maturity Model Integration
CNC	Computer Numerical Control
CPPS	Cyber-Physical Production System
CPS	Cyber-Physical System
DCS	Distributed Control System
DREAMY	Digital REAdiness MaturitY model
DSL	Domain Specific Language
ECCMA	Electronic Commerce Code Management Association
eOTD	ECCMA Open Technical Dictionary
ERP	Enterprise Resource Planning
FAR-EDGE	Factory Automation Edge Computing Operating System Reference Implementation
FIFO	First-In-First-Out
HoMoCPPS	Holistic Migration approach towards CPPS
IBD	Internal Block Diagram
IMC-AESOP	Architecture for Service-Oriented Process – Monitoring and Control
IML	Interdisciplinary Modeling Language
INCOSE	International Council on Systems Engineering
IoT	Internet of Things
IP	Internet Protocol
IT	Information Technology
KPI	Key Performance Indicator

LAN	Local Area Network
LML	Lifecycle Modeling Language
MASHUP	MigrAtion to Service Harmonization computing Platform
MBSE	Model-Based Systems Engineering
MES	Manufacturing Execution System
MOMOCS	Model driven Modernization of Complex Systems
PDCA	Plan-Do-Check-Act
PERFoRM	Production harmonizEd Reconfiguration of Flexible Robots and Machinery
PLC	Programmable Logic Controller
RAMI4.0	Reference Architecture Model Industry 4.0
SCADA	Supervisory Control And Data Acquisition
SE	Systems Engineering
SLA	Service Level Agreement
SOA	Service-Oriented Architecture
SOAMIG	Migration of legacy software into service-oriented architectures
SMART	Service Migration and Reuse Technique
SysML	System Modeling Language
TCP	Transmission Control Protocol
TPS	Toyota Production System
TRL	Technology Readiness Level
UCD	Use Case Diagram
UML	Unified Modeling Language
UNSPC	United Nations Standard Products and Services Code
VDI	Verein Deutscher Ingenieure
XIRUP	eXtreme end-User dRiven Process

1 Introduction

Over the past few years, the need for migration strategies is one of the most popular topics in the industrial manufacturing sector, especially within the framework of Industry 4.0 [KT16a]. This new industrial paradigm represents the fourth industrial revolution, which is going to force organizations to move towards digitalization and transform their legacy production systems in order to stay competitive in the market [KWH13]. This chapter investigates the origins of changes in industry and the motivation behind the scope of the thesis, underlying the hypotheses that guided the research.

1.1 Problem Context

Industries have been subjected to technological radical changes different times evolving from mechanization through automation. Having a look at the history, every major industrial change in terms of new economy marked by the transformation to new manufacturing processes is commonly referred to as “industrial revolution” (Figure 1-1).

Between the 18th and 19th century the introduction of machines, the use of water power and steam power for production began the first industrial revolution, based on “mechanization”. The consequence of mechanization in production was twofold: on the one side the new machines required a large amount of labor and energy due to the increased volume of output produced and the high number of manual tasks, on the other side new forms of manufacturing grown driven by the need of new resources, such as, textiles, steel, and tools. In the end of the 19th century there was a second industrial revolution, referred to as “mass-production”, characterized by the introduction of electricity, which powered the large-scale manufacturing of machine tools and the first assembly lines. Driven by the need for massive industry, this industrial change resulted in a higher level of specialization and interdependence in manufacturing. New organizational and management approaches evolved into large-scale business operations over vast areas. Industrial and manufacturing engineering, as well as business management, contributed to the complete reconstruction of factories’ operations, and later also the entire economy sector. In addition, the envisioned industrial and organizational models of production by Taylor and Ford put emphasis on the importance of training and developing employees and distributing work almost equally between management and workforce. An important outcome of this revolution was also the lowering prices of almost all goods. In 1970s, a third industrial revolution of “automation” took place with the rise of electronics, telecommunications and computers. This revolution is characterized especially by the use of high-level automation systems into production process, such as programmable logic controllers (PLCs) and heavy-duty industrial robots, to advance automation and motion control in manufacturing. As a consequence, new skills for the factory workers were required, e.g. computer programming knowledge. Moreover, the revolution has been influenced by the integration of computers in the factory planning and production processes and the introduction of Six Sigma and Lean Management concepts [Te01].

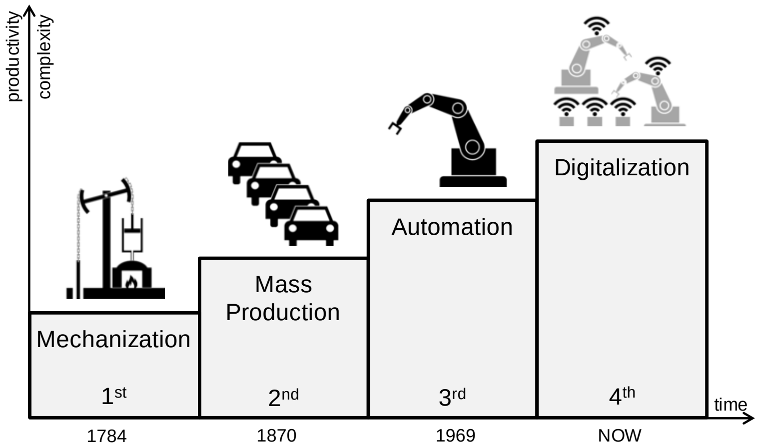


Figure 1-1 The four industrial revolutions (adapted from [Ro15])

Right now we are facing the fourth industrial revolution of “robotization” and “digitalization” [KWH13] based on Cyber-Physical Systems (CPS) [Le08] and the emergence of the Internet, which is going beyond automation and optimization towards artificial intelligence [ac11]. Industries need to be prepared to another radical change in order to stay ahead of the marketing trends considering the particular importance of the driving forces of the revolution. In fact, the former revolutions were driven not only by the actual internal options in terms of technologies and work environment but also by external influences, like trends and globalization, governmental policies and the economic context. Within the first revolution the main driving force was the better quality of life derived by the substitution of human and animals’ labor with machines. The division of labor in the mass-production revolution changed the industry’s organizational structure, while the low transportation costs derived from the mass-production enabled the globalization, resulting in lower resources’ costs in the automation revolution.

As the same, [ac11] highlights that current market forces and the increasing demand of customers for personalization drive the fourth industrial revolution more than the innovative and advanced technologies. Industries need to quick adapt to innovation to stay competitive in the market. According to [GT10], with today’s rapid technological change successful companies have a tendency to fall into three *traps*. There is the *physical trap*, due to the investments already done on the legacy infrastructure that prevent other investments on new technologies. The *psychological trap*, when the company's current success prevents company leaders to consider new opportunities. And the *strategic trap*, when the company focuses only on the today's market without anticipating the future. A classical example of business failure is Kodak, which vanished because did not adapt to the technological improvement that rapidly shifted from film-based to digital photography. Other examples of big companies that failed because did not adapt to innovation are Blockbuster, Nokia, and Polaroid [Co14b]. This makes clear that innovation, i.e. the current digital transformation, impacts every industry.

Existing industries can take advantage of this revolution only if they are able to meet the new market demands and innovative technology within the frame of their working environment [VD15] and investment capabilities [PR17].

In the context of digitalization and cyber-physical systems, factories cannot be considered as single autonomous entities not being impacted by the external environment in which they operate [TTC17]. Technologies play an important role in the transition from an industrial environment to the next revolution, but the entire complex ecosystem affects also a number of players and stakeholders, i.e. social, organizational and business parts. For this reason, there is a strong need for holistic methodologies and techniques that support the transformation, i.e. migration, of existing industries from the "automation" era towards the "digitalization" and "robotization".

1.2 Motivation and Scope

The term "Migration" refers to the transformation of an old system into a new one (Figure 1-2). More specifically, it is the changing process from an existing condition towards the desired one. Within this thesis the purpose of migration is the gradually changing process of the traditional industry based on the "automation" towards "digitalization" [KWH13].

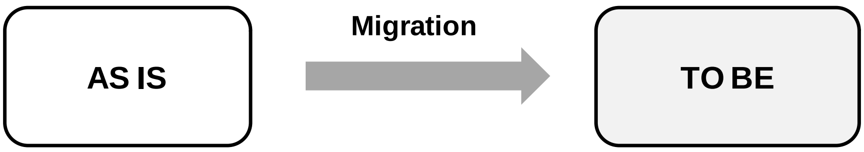


Figure 1-2 Concept of Migration

The paradigm of digitalization touches different domains (see [ac11]). This thesis focuses only on the manufacturing domain and considers the migration as a progressive transformation that moves an existing production system towards Cyber-Physical Production Systems (CPPS), described in [Mo14], [BL15], by changing and improving not only the implemented technologies but also the ecosystem around them. CPPS are here defined as networks of independent CPS creating a comprehensive, dynamic and changeable production system based on a high degree of cross-linking of all involved systems that represent an autonomous and intelligent production unit [SH16].

To remain ahead in a highly competitive market, a rapid technology change towards a more flexible and adaptive production system is necessary. However, the adoption and implementation of the next generation technologies and intelligent devices is perceived as a very complicated and expensive task. Manufacturers have already invested a lot on their legacy systems and now they will probably need to modify or adapt them in order to be integrated to the new ones. Today some companies have invested in a few of these technologies [Rü15], but missing pilot projects and full real industrial implementation lead to a lack of trust and confidence on some intelligent technology solutions.

Industry 4.0 is defined as a disruptive revolution, generating a certain sense of urgency within manufacturing companies [GB17]. As a consequence it is often assumed that to stay ahead in the market, an entire shift over of their production into a digital-based system is necessary. But, in reality, a complete digital overhaul is very difficult to undertake.

It is extremely important that manufacturers understand that such a Big Bang approach is avoidable. Instead, they should implement Industry 4.0 through a stepwise approach. This means prioritizing areas in which digitalization and robotization would offer the most benefit. The advantage of this approach is that the solid foundations of technology, infrastructure and skills can be laid, facilitating the final move into the so called “Smart Factory” [Zu10].

Following these argumentation, the aim of this thesis is to support the migration of manufacturing industries from the third to the fourth industrial revolution with a pragmatic and stepwise approach defined within the frame of two EU Horizon 2020 research projects: PERFoRM [PE15] and FAR-EDGE [FA16].

This thesis aims at answering the main research question “*How to derive migration strategies towards Cyber-Physical Production Systems?*”.

The proposed solution should support manufacturers in creating the basis for a successful digital transformation from traditional manufacturing industries towards flexible and reconfigurable production systems, according to the Industry 4.0 paradigm.

As stated above, several technologies have been developed so far to enable CPPS but they are still rarely used. The implementation of digital innovation requires a change in the entire factory but this change has been always ignored or underestimated. The upcoming fourth industrial revolution requires a change in manufacturing in terms of technology, but also infrastructure, skills, and business models.

This research has been guided by the underlying hypothesis that technical and business risks, due to the implementation and integration of smart systems and intelligent devices within an existing production environment, cannot be avoided but can be mitigated if aspects related to the operational activities, organizational structure and market demands are considered within the migration planning. Therefore, the focus of this thesis is not only on the technical migration itself, but on the large effect of this change in a factory.

The proposed stepwise approach provides manufacturers with a holistic engineering approach that supports the incremental improvement of their systems towards Industry 4.0. The approach is based on the lean and agile methodologies, to ensure the continuous and incremental improvement of the production system into CPPS, and supported by maturity models and model-based systems engineering techniques to keep a holistic view on the system evolution in its completeness, i.e. considering the impact of change on the different dimensions of a factory. To validate the applicability of the proposed solutions an industrial case is examined.

The case study concerns the manufacturing of customized compressors for the oil and gas industry. The goal is to produce small lot sizes in an increasingly changing environment with high customer demands. The challenge within the case study is to demonstrate the potential of the Industry 4.0 solution for cyber-physical production systems in terms of reduced cost and increased product delivery reliability and ability to react to changes.

The approach has been applied also to other industrial use cases within the two European research projects.

1.3 Thesis Outline

A graphical summary of the structure of the thesis is represented in Figure 1-3.

After this initial introduction of the thesis, Chapter 2 starts with a deep look into the fourth industrial revolution. Here the main technologies that are driving the new vision of factory based on cyber-physical systems and the Internet of things are described with a special focus on the automation control architecture. Moreover, an analysis of the transformation process towards the new smart factory concept is provided. The analysis highlights the need for holistic migration strategies through the investigation of the possible impact aspects at technical, operational and human dimensions on existing production environments. The chapter concludes with a set of derived characteristics for migration process towards digitalization and robotization.

Chapter 3 provides a literature review of processes and methods that can be related to the migration process towards CPPS. First the concept of engineering process is introduced, since the migration towards CPPS implicates the re-engineering of existing production systems. Then, the available migration strategies and processes developed in past research projects and in different domains, ranging from software and data migration to automation architectures and modernization processes, are reviewed and compared.

Chapter 4 focuses on other engineering practices supporting the management of the strategic transformation of an organization in terms of system improvement and optimization. First, lean and agile methodologies are analyzed pointing out the benefit that can be derived from the merger of both approaches for the definition of a migration process within a manufacturing context. Second, capability maturity models are considered as commonly used to understand the digital readiness of an organization. Finally, an outlook on modeling techniques for system representation related to the object-oriented modeling for systems engineering applications is provided.

Chapter 5 shows the current gap that motivated this thesis work within the context of migration processes able to support industries' transformation towards the next industrial revolution. Here three main research questions that need to be answered in the following chapters are defined.

Chapter 6 describes the proposed solution concept. The first section illustrates the principles, while the second section describes the logic behind the general migration approach towards CPPS. The third section provides an overview of the 5-phases of the proposed holistic migration process. Their embedded methods and tools are described in the final section.

Chapter 7 discusses the application and implementation of the migration approach to the industrial practice. The approach, process, methods and tools are applied to the previously described industrial use case. The results, as well as the benefits, of the proposed holistic migration approach are shown within this chapter.

Chapter 8 concludes the thesis with a final summary of the answered research questions and the research's results, providing also an outlook to possible future work.

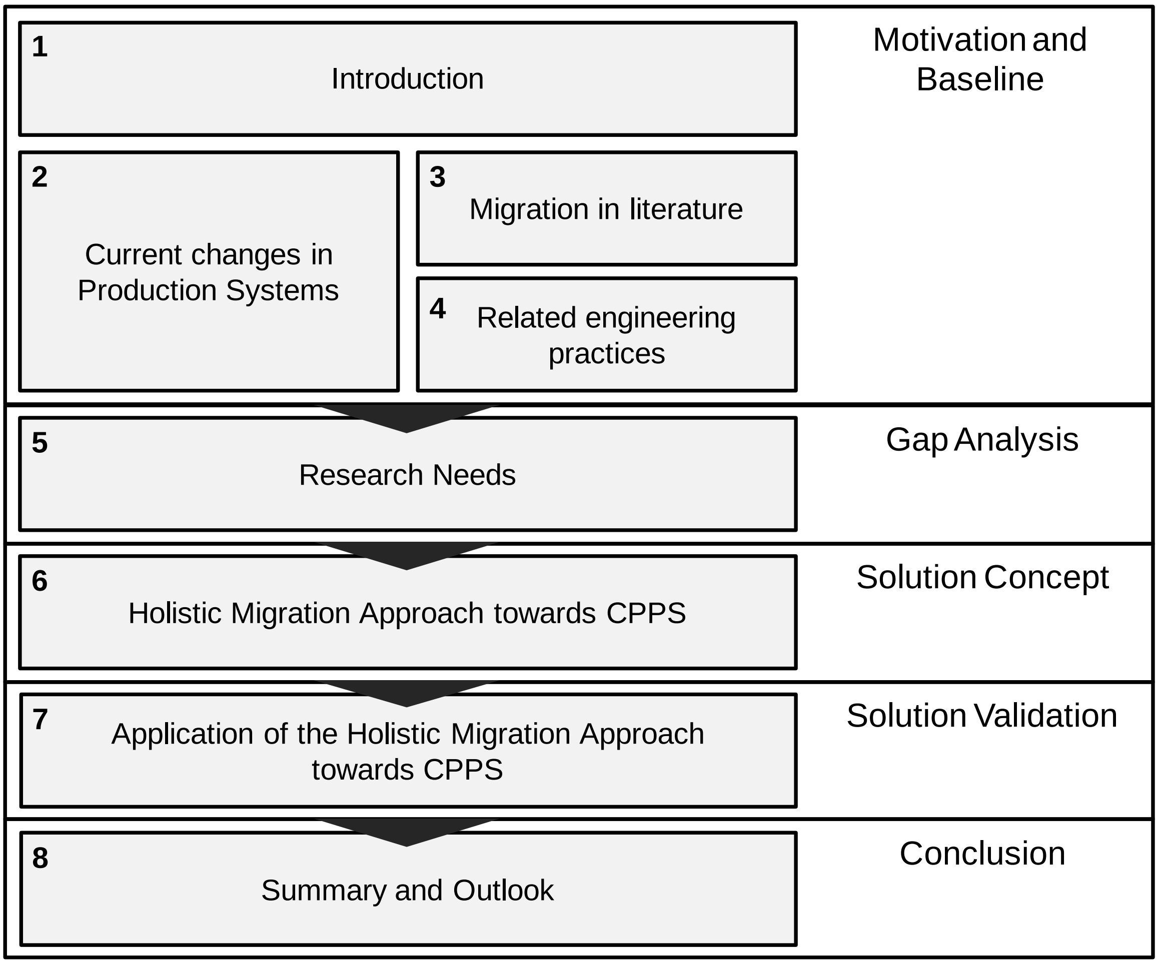


Figure 1-3 Structure of the thesis

2 Current Changes in Production Systems

Industrial revolutions are referred to as the radical transition to new manufacturing processes, different organizational structures and the use of unprecedented technologies. Right now industries are facing the fourth transformation towards the digitalization and robotization of production systems. This chapter describes the next industrial revolution in terms of main innovative technologies involved and the required evolution of the automation control architecture to enable flexibility and reconfigurability of the envisioned Smart Factory. As remarked in the previous chapter, the industrial revolution affects not only physical equipment and technologies but also the entire production environment, including the production organization and its market context. New value creation strategies are necessary to adapt production to customers' requirements. Here the main impact aspects of the digital transformation of an existing production system are analyzed and, therefore, the characteristics of this transformation process are derived.

2.1 Towards "Industry 4.0"

Today markets require shorter product life cycles and time-to-market, while increased product variety. The generally accepted and well known German term "Industry 4.0" refers to a paradigm that aims at increasingly smart systems for flexible and reconfigurable production systems based on the vertical and horizontal integration of the value chain, able to cope with these market requirements.

Kagermann et al. [KWH13] stated in 2013 that Industry 4.0 initiative will involve *"the technical integration of Cyber-Physical Systems into manufacturing and logistics and the use of the Internet of Things and Services in industrial processes"* and provide *"fundamental improvements to the industrial processes involved in manufacturing, engineering, material usage and supply chain and life cycle management"*, resulting in *"implications for value creation, business models, downstream services and work organization"*. Although there is no standard definition, the one mentioned above can be considered as the main vision of the Industry 4.0 concept also within this thesis. Similar definitions can be found in literature, such as in [Ma14a], [DD16], [UC18].

As promoted by many authors, like [Rü15], [ac11], [GVS16], [Je17], this initiative will ensure in manufacturing new capabilities, such as, autonomous decision-making, interoperability, agility, flexibility, efficiency and also cost reductions [VOL17]. In addition, Industry 4.0 goes beyond the factory enabling also other correlated phenomena, namely smart grid, smart logistic and smart buildings [GVS16].

Influenced by the market competitiveness and new customer requirements, many companies are aiming at implementing the new technologies and concepts of the Industry 4.0, as shown by the PricewaterhouseCoopers (PwC) survey results [Mi16]. According to [GJ13] this goal is driven especially by their customers, which require not only lower prices but also more variety, higher quality and faster delivery of the product. These requirements result in an increasing demand for more production with less wastage and more efficiency.

Besides the demand-pull, also a strong technology push has an influence in this context [BLG17]. New developed intelligent technology concepts, such as autonomous robots, additive manufacturing, cloud computing, and augmented reality, will be leveraged to realize smart factories able to satisfy current market requirements (Figure 2-1).

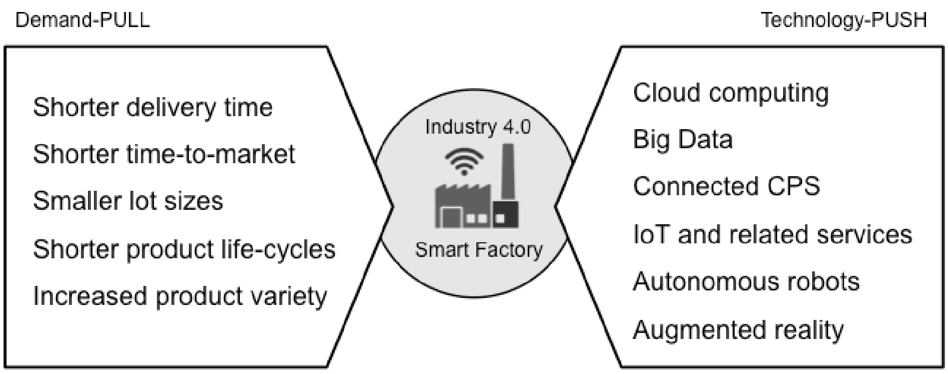


Figure 2-1 Smart Factory

Compared to the traditional automation, the Smart Factory concept [Zu10] of the fourth industrial revolution goes one step forward to flexible and reconfigurable production systems adaptable to continuous changing requirements. The smart factory is based on Cyber-Physical Systems (CPS) [Le08], which represent the integration of physical systems and their virtual description. By integrating data from physical, operational and human assets, a smart factory can drive manufacturing activities across the entire manufacturing network, resulting in a more efficient and agile system. The communication between these different systems and applications is enhanced by the Internet of Things (IoT), which refers to "*a network of physical objects that are embedded with electronics, software, sensors, and network connectivity, and are able to collect and exchange data*" [IT12]. This large collection of complex data sets, called Big Data, cannot be managed by traditional data processing systems. Thus, the term Big Data analytics has been used by [SS12] to refer to analytics based on the large amount of data collected from physical systems for analysis, enabled by CPS and IoT technologies.

Indeed Big Data analytics is characterized by the big volume of data, the wide variety of data types and the velocity required for data processing. Moreover, data can be collected, stored and managed by means of Cloud technology [Ba12], which has been extended to the manufacturing context to enable different stakeholders to access computing resources over the Internet in real-time. Besides the information and communication technologies also intelligent equipment, such as autonomous robots and devices for augmented reality, play an important role in the Smart Factory vision. Research activities in advanced robotics developed autonomous and cooperative robots able to interact with each other and to get involved in all production stages on the basis of sensor data [Bİ18]. On the human-machine interface side, augmented reality solutions can integrate information supply into the workflow [DD15]. They consist in displaying relevant and supplementary information of processes as a virtual graphic over physical objects via data glasses, wearable technology or dynamic touch surfaces.

These are just few of the numerous Industry 4.0 technologies for manufacturing. More details on this topic can be found in literature, such as in [WCZ15], [LCK16], [Je17], [Zh18] and [UC18]. McKinsey&Company divides the main technologies that will enable the digitalization of the manufacturing sector in four clusters, as shown in Table 2-1:

Digitalization of the manufacturing sector – Industry 4.0			
Data, computational power, connectivity	Analytics and intelligence	Human-machine interaction	Digital-to-physical conversion
• Big data / open data • Internet of Things / M2M • Cloud technology	• Digitalization and automation of knowledge work • Advanced analytics	• Touch interfaces and next level GUIs • Virtual and augmented reality	• Additive manufacturing • Advanced robotics • Energy storage and harvesting

Table 2-1 Main technologies that will enable the digitalization of the manufacturing sector [Mc15]

As described in [Mc15], technologies of the "Data, computational power, and connectivity" cluster allow for autonomous communication among all physical objects of the production environment. Knowledge advances in the "Analytics and intelligence" cluster foster machine learning and knowledge-based activities thanks to improved statistical techniques. The growth in "Human-machine interaction" comes from the increased use of personal devices in the every-day life. Technologies of this cluster are used to lighter repetitive human tasks. Finally, "Digital-to-physical conversion" cluster comprehends those smart devices that convert physical information into the virtual word.

Even though some manufacturers are already using some advanced technologies, such as the use of real-time production data for planning and scheduling based on real-time production data or augmented reality for maintenance, the realization of a smart factory consists in a more radical and holistic change. If on one side the technological trends focus on the proliferation of IT systems and smart objects in the factories, on the other side they lead to the interconnection of these systems, exchanging information with each other thanks to their embedded computing power and communication capability. Naturally, the implementation of intelligent equipment and advanced technology implicates also the integration of new functionalities into old legacy systems.

Today the communication flow from the shop floor to the operational applications is very limited due to the centralized structure of the information and control system. Conversely, the envisioned Cyber-Physical Production System (CPPS) are based on decentralized automation control architectures to enable the communication and data exchange between various heterogeneous systems in the shop floor and operations management through standard mechanisms [Su17], [GJ13]

Therefore, the success of the Industry 4.0 horizontal and vertical integration strongly depends on the information and communication technology architecture for automation and control of the production system. In order to achieve flexible and reconfigurable production systems and enable faster reaction to changes, a large amount of data should be available and stored at any convenient location. This aspect immediately leads to required regulations and compliant standards across all the domains of plant operations.

2.2 Industrial Automation Architecture

The control architecture is a key factor for the final performance of the application system [RD84]. Today industries need to change their production approach in order to be more flexible to different processing tasks, adaptable to changing production environment, and reconfigurable to enable these changes while maintaining their security, safety and stability [ZV15]. The traditional automation control systems in production cannot provide industries with such capabilities because they are based on a rigid and top-down communication flow that prevents the integration of new modules and systems, thus the required flexibility and reconfigurability.

2.2.1 Centralized automation architecture

The state of the art production systems are described by centralized and hierarchical control system architectures, such as the automation pyramid, based on the ISA-95, and IEC 62264 standards [AN110]. According to these standards, the actual conventional automation pyramid presents a clear separation of systems and functionalities in five automation levels that have their own specific automation purpose (Figure 2-2 a) and exchange information only with the adjacent layers.

This hierarchical control structure supports operational tasks at different levels of information within a plant, such as production planning and scheduling, production data acquisition and processing, equipment and material flow control [RD84]. The architectural structure is referred to a pyramid because the systems located at different levels refer to different time ranges. Time frames at higher level range from months to weeks, while the lower levels range from days to seconds and milliseconds.

Three basic control levels can be distinguished (Figure 2-2 b). The highest level of the pyramid represents the business management of the enterprise, e.g. economical and logistic activities such as production scheduling and operational management. The intermediate control level includes coordination and management activities of the production execution and the integration of systems in terms of main data workflow within the plant. The lowest level consists of modules related to the control of product and process technologies, to the monitoring of the overall production system, and to the measurement and display of equipment data by using actuators and sensors.

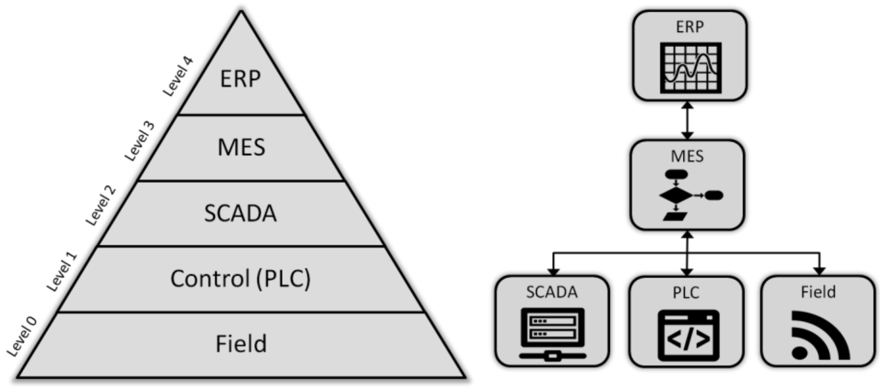


Figure 2-2 Automation Pyramid: a) functional view b) structural view [Fo17]

The ISA standard [AN313] formalizes the interactions of these hierarchical levels to enable automated communication between enterprise planning and shop floor control systems [AN513]. A hierarchical structure presents high robustness and emphasizes a good predictability and system global optimization.

On one side this structure is effective for small systems running in very stable and structured environments, in which the ISA-95 pyramid characteristics of easy development and maintenance can be exploited [Sc07]. The hierarchical approach is beneficial in terms of providing a one-to-one mapping of logical control into physical architecture, thanks to the limited size, functionality, and complexity of individual control modules [RT88].

On the other side, the hierarchical structure of the automation architecture creates a master-slave relationship between different levels of control. This dependability between control levels results in insufficient adaptability and flexibility to production changes. Moreover, a single point of failure can dramatically reduce the system performance. Information becomes also inconsistent and obsolete as soon as a communication delay occurs, which negatively impacts on partial and global decision-making. As a result of these limitations, a centralize structure cannot sufficiently deal with dynamic adaptive control and resource sharing.

In conclusion, due to modern information technologies, the traditional automation pyramid needs to evolve from centralized to decentralized control architecture. In order to quickly change production equipment and functions according to customer demands and new market requirements, a more seamless integration of the traditional hierarchical control levels is required.

2.2.2 Distributed automation architecture

Beside the automation pyramid, other structures of the control architecture have been defined, such as the reshaped automation pyramid from Vogel-Heuser, according to [VSG15], or the Smart Grid Architecture Model (SGAM) presented in [GUD17], and of course the well-known RAMI4.0 [VD15].

Lot of research has been conducted towards the decentralization of automation by using innovative technological approaches, such as multi-agent systems (e.g., [Wo02], [LK15]), web services and service-oriented architectures (e.g., [WA11], [SSB11], [CK09]), plug-and-produce technologies (e.g., [OMD13], [An14]), and cloud computing (e.g., [Co14a],[Co14a], [SLS15]). A comprehensive analysis of the state of the art distributed automation architectures is reported in [PE16a], [CaF16] and [Fo17]. The main goal of distributed automation architectures is to enable the communication of all elements in a production system in order to facilitate and accelerate the decision-making process in production control operations [MIA17].

A general representation of the envisioned distributed automation architecture [Fo17] is given in Figure 2-3, which is based on an integration layer, or middleware, that enables the integration of production equipment (e.g. Robots, PLCs, CNC machines, etc.) and applications (e.g. ERP, MES, databases, simulation tools, etc.) through standards interfaces and technology adapters. The adapters are meant to adapt proprietary interfaces to standard service interfaces through a service wrapper, enabling the communication and information exchange between different production system elements on the basis of a common language.

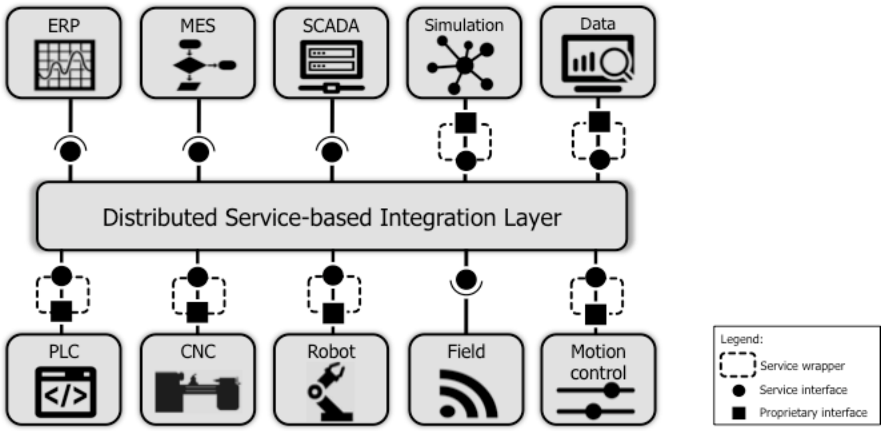


Figure 2-3 Distributed automation control architecture [Fo17]

Several advantages are associated with this kind of architectural structure, which meets the production industry requirements of fast reaction to rapid changing conditions by achieving more flexibility, higher efficiency and overall adaptability in automation systems [Mü16]. Real-time information is fundamental to more agile manufacturing operations. In contrast to a hierarchical architecture, in distributed architectures the lack of multiple levels of control facilitates the fast communication and data exchange between different elements in the production system [MIA17]. Without multiple levels of control, also the master-slave relationship disappears resulting in faster control response of production elements, thereby becoming autonomous.

Hence, in a distributed automation control architecture all autonomous elements are able to process information and make decisions [TBT16]. This results in an improved system performance thanks to self-* capabilities conferred to production systems, which support systems integration, control and monitoring, as well as cooperation and adaptation [Fo17].

For example these control architecture characteristics can result in providing not only rapid reconfiguration capabilities [An14] but also self-diagnosis capabilities to shop floor equipments enabling a distributed diagnosis of the system and thus manage unexpected behaviors [OMD13]. Self-learning capabilities enable the reconfiguration of shop floor machines and processes based on the experience acquired during the system routine [SSB11]. Self-healing capabilities maximize the production systems performance over longer life times [SLS15].

Moreover, the use of open standards enhances the collaboration among various stakeholders enabling the vertical and horizontal integration within a factory according to the Reference Architecture Model Industry 4.0 (RAMI4.0) [VD15], [ZV15]. With the advent of cyber-physical systems the interoperability is considered a very important topic in engineering [DLH11].

In conclusion, the need of flexibility, adaptability and reconfigurability has been emphasized already in [DBW91] as the main goal in the design of control systems architectures. Production units need these capabilities to cooperate and organize themselves in order to optimize the production systems, saving time and cost. The hierarchical control architecture based on the ISA-95 automation pyramid still represents the state of the art automation architecture because of its established advantages in manufacturing industry. However the abilities mentioned above are limited in a rigid communication structure. The emergence of many distributed control architectures highlighted the need to transform the automation pyramid into a modular and flexible automation system architecture with decentralized control systems, which enhance real-time performance by enabling integration and cooperation of production system in a cross-layer manner, like in the architecture proposed in [Fo17].

2.3 Impacts of Change

As mentioned in Chapter 2.1, organizations and initiatives like acatech [www.acatech.de] and Plattform-I4.0 [www.plattform-i40.de] highlighted that industries will benefit from digitalization in terms of connectivity of plant floor to enterprise, web access, remote diagnostic, improved machine uptime and reduced downtime, reduced engineering costs, etc. All these things encourage industries to migrate towards the paradigm of digital smart factory. However, manufacturers need to take into account also risks and obstacles related to the implementation of these new technologies in their existing production environments.

Although lot of research has been done within the frame of Industry 4.0 technologies and intelligent systems, the transformation towards digitalization cannot be easily performed due to its huge impact on other aspects of industry.

The technology solutions available today to trigger the digital transformation in manufacturing are numerous, but different technologies have different impacts on the production system. These impact aspects, represented in Figure 2-4, vary according to the industrial domain, size of the factory, type of product, and production processes. Therefore, the factory migration plan towards CPPS is driven by the company's strategy as well as by the impact of these new technologies and infrastructures on an existing production system, here considered as collection of people, equipment and processes organized to complete the production activities of a company [Gr07].

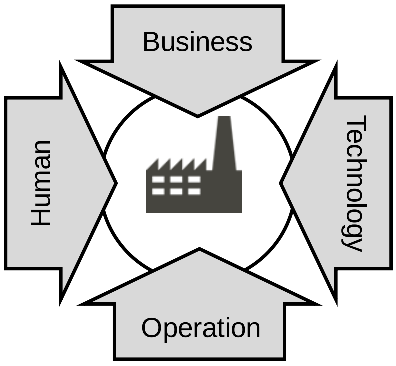


Figure 2-4 Dimensions of change impact aspects in a factory

Opportunities and challenges of Industry 4.0 and Cyber-Physical Production Systems are clustered below in business strategy and technical, operational and human dimensions of a factory.

2.3.1 Business strategy

The introduction of CPPS poses a big challenge for the vast majority of existing companies because it involves different layers of the enterprise architecture at the same time, i.e. technology, organizational structure, business model, etc. This change requires indeed adjustments at both engineering and business levels.

The vertical and horizontal internet-based integration of people, machines and software applications of the Industry 4.0 fosters the dynamic management of complex business processes [MKV18]. Production networks with decentralized control have numerous business potentials in terms of shorter lead times and accelerated time-to-market, related to high cost reductions.

Besides the existing production processes, industries need to further develop new business models based on changes to production, products and services [OFM17], [PI16]. For example, Manufacturing as a Service (MaaS) is an emergent business model based on digitalization and robotization. This business model consists in the shared use of networked manufacturing system to offer customers high level of personalization for different types of products [MSN15].

However, the development and transformation of existing business models is often perceived by companies as a challenge rather than an opportunity [OFM17] because of the difficult evaluation of risks and opportunities of CPPS. As written in [Su17], strategies and operations need to be fully understood by all the stakeholders to ensure the successful development of new business models. Standardization, such as the successful eCl@ss, UNSPC, and eOTD standards for products and services [HLS07], can help in this direction, enabling the unambiguous description of stakeholders' requirements and business strategy characteristics.

A few approaches for developing business models in a CPPS context can be found in literature, especially in [Ru14], [SSL14], and [FWW14].

Costs and benefit of future implementation of Cyber-Physical Production Systems need to be evaluated to assess the potential of business innovation [Ru14]. In fact, cost is one of the key aspects in the adoption of new technologies. Costs comprehend not only the acquisition of new equipment, application and infrastructure, but also the development, deployment, maintenance, management, and human training. Moreover, current costs on legacy systems need to be taken into account before investing in new technologies and consider their impact on the return of investment. This is not easy to evaluate since, although the benefit at technical level has been proved in several research activities and industrial application, the economical profitability is still unclear and difficult to quantify in advance [KL16].

2.3.2 Technical dimension

The technical dimension has an important role in the production system migration. Industry 4.0 leads to a production system based on automation and CPS to enable the fast reconfiguration of a modular shop-floor, i.e. with plug-and-produce equipment control, to fast adjust production processes according to required changes. Flexible and reconfigurable automation systems need to be technologically mature enough [IE15] to both guarantee the performance needs of the system and get accepted by industrial decision-makers [KL16].

Industry 4.0 is based on a Cyber-Physical Production Systems infrastructure in which heterogeneous systems cooperate by using and exchanging the globally available information of production equipment and business processes [DD16]. Therefore, the integration of heterogeneous hardware system, software applications and legacy systems is a key factor, which requires a huge effort to be implemented. In fact, the successful implementation of Cyber-Physical Systems in manufacturing is highly dependent to the automation control that will manage the communication network of the systems.

Main aspect is thus to ensure the interoperability of smart CPSs as well as their compatibility with the legacy systems as new technologies are usually integrated into an existing operational environment that has to be aligned with new infrastructure. To this end, the traditional shop-floor equipment has to be updated and new digital communication standards need to be adopted to enable the orchestration of new and old systems [Je17]. Standardization is important for systems interoperability but also to allow work collaboration, such as in the description of requirements and system specifications from different stakeholders in an unambiguous manner [Su17].

The link between digital and physical worlds supports the acquisition and treatment of production equipment data in order to better observe and change or optimize a production process by changing an automation workflow. To this end, the bilateral communication is enabled via sensors and actuators and systems equipped with additional network connection capabilities (e.g., PLCs). This connection implies computing devices connected to a fast LAN and information and communication technology platforms (e.g. middleware) to enable the wired and wireless communication among physical components, electronics and software.

2.3.3 Operational dimension

Industry 4.0 enables also several new operational opportunities, such as intelligent scheduling of tasks and processes based on the prediction of machines' failures, leading to improved production lifecycle management [MKV18]. Smart technologies, e.g. additive manufacturing and 3D-printing, enhance reduction of waste and resource consumption in production and logistics processes.

Virtual simulations of production activities and tests of what-if scenarios facilitate process optimization without impacting regular shop-floor activities [MKV18]. To this end, synchronized digital models of plant and processes can support simulation either through complex algorithms or by using shop-floor data directly. In combination with machines self-awareness and monitoring capabilities, production systems can autonomously modify production processes based on certain parameters' values or in order to fulfill changed requirements. These capabilities can be used to improve product quality continuously [Er16], [MKV18].

In addition to intelligent manufacturing technologies, aspects of different nature need to be considered. For example, services of factory Cloud that run in a digital computing environment can turn in accesses for external software applications, internally available utilities, or store analyses and simulation results. Therefore, security techniques currently in use need to be extended to protect CPPS in their end-to-end operations from possible attackers due to their hybrid, distributed, and system-of-systems nature [Zu10]. Also, user permission and identity management within operational activities need to be addressed to ensure only authorized access to the factory plant system for privacy and data protection.

2.3.4 Human dimension

The transformation of production systems and processes has an impact also on the organizational structure of a company, in which different stakeholders are involved, i.e. from technical operators to engineers and factory managers. Therefore, the success of the introduction of CPS is strongly related to the acceptance by users [ac11], [KWH13]. People need to be motivated to participate to the production system transformation to help the successful results of migration. Usually people resist changing their current tasks, since they perceive such new activities as additional efforts besides the usual tasks, thus educational and integration activities need to be considered from higher-level management to clarify the resulting benefit and motivate them to adopt the new technologies.

As stated in [Zu10], the new structure of the distributed automation architecture implies a need for new engineering methods and tools. Therefore new mindsets and ways of thinking to handle the digital transformation are thus required in the organization, as well as strategy for addressing employees qualification and acceptance are necessary [MKV18]. As lesson learned from the third industrial revolution, the successful implementation of information technology is correlated to the involvement of the affected personnel within the change process [Sc17]. People must have confidence in the new information systems and processes and this is possible only if they understand the new technologies they are going to use. It worth's saying that people play a key role to enable the new production scenario, so hire skilled staff to keep the know-how is very helpful to maintain, and even evolve, the new production environment [KT16b].

Industry 4.0 will fundamentally change work and processes. In the future, a replacement of simple tasks is expected due to the implementation of intelligent devices and autonomous robots. However monitoring, collaboration and training will be still required [MKV18]. The factory employees will have to take on more responsibility when it comes to coordinating processes, steering communication and taking autonomous decisions. The tasks will be more challenging, technologically as well as organizationally, and interdisciplinary competences will gain importance [An15]. A system-of-systems perspective can be, thus, supported by the integration of know-how from different disciplines, which can be merged in new roles, e.g. systems engineers [IE15].

Moreover, new job profiles addressing risks related to IT security, safety, privacy and knowledge protection need to be considered in training and education programs [PI16], [LCK16]. To this end, Digital Innovation Hubs can be a good instrument to encourage people to study this kind of disciplines and reinforce some of technical development activities to make possible the digitalization of industry.

2.3.5 Conclusion

To summarize, the implementation of Cyber-Physical Production Systems needs to take into account different impact aspects in order to be successful, in terms of providing benefits to the factory and supporting the migration towards the digital innovation of the Industry 4.0 vision [Ka09], [KWH13]. Smart solutions, digital systems and standard communication protocols impact on an existing production system also on its performance, work organization, and business strategy. Manufacturers need support to understand how the transformation towards CPPS affects the overall production ecosystem under all these aspects, which need to be analyzed together and simultaneously in a holistic approach. In fact, as stated by Oks et al. in [OFM17], it is quite impossible to take into account all the difference factors at the same time without a systematic approach.

The migration towards CPPS is more than just the deployment of smart technologies and the movement of data from a database to the cloud, but inevitably brings a broader impact to the factory business change, which occurs from the operational and human viewpoints. Therefore, the migration must be implemented as a changing process that requires an understanding of issues and entities involved at technical, operational and human levels [St04]. In addition, it has to be driven by business change goals in order to make optimal decisions on what migration targets to follow and what appropriate migration strategy to select [St11]. As a consequence, the communication and cooperation between the business and technology managements are fundamental within a migration process.

2.4 Required characteristics for migration

The change from the third to the fourth industrial revolution in production is costly and full of uncertainties. An industrial company usually deals with a difficult decision-making process related to changes of the current production systems in order to constantly improve and stay competitive in the market [NNO08].

As mentioned in Chapter 2.3, several migration options can be generated if different impact aspects are considered. A trade-off analysis of the migration options is necessary to identify the optimal migration strategy according to the business goals of the considered company. These aspects are usually very correlated to each other, leading to the need of an extremely careful migration process that mitigate risks due to the implementation and integration of new equipment and applications into an existing environment. Also, new information technology also requires new human skills.

Therefore also educational and training programs need to be considered within the definition of the migration strategy.

Manufacturers need to understand how to deal with the upcoming Industry 4.0. The migration approach should help them in identifying what is the optimal strategy to transform their own specific production system taking into account business goals, technical constraints, production processes and human skills.

Some migration processes already exist in literature and are described in Chapter 3. In order to analyze and compare them, some requirements related to the transformation towards the next generation of production systems need to be identified. This section defines a set of requirements for a migration process, derived from literature, in order to support manufacturing industry in adopting digital technologies and move towards the Industry 4.0.

1. The first characteristic expected for a migration process towards CPPS and the Industry 4.0 paradigm, which is still perceived by manufacturers as unclear and uncertain [Pw16], is to implement the new system *step-by-step*. In fact, a smooth approach of system changeover can minimize risks by implementing the target system in small portions at a time. The stepwise implementation is meant to smoothly prepare a production system for future CPPS-compliant configurations starting from solving current challenges and improving current situations, in order to provide quick benefits that make manufacturers understanding the advantage of Industry 4.0 solutions [KT16b]. Therefore, the characteristic of being stepwise is not sufficient but must be further specified by the following require characteristics for migration approaches: iterative and incremental.
2. Since radical changes are characterized by high investments, technologies and market uncertainty, they require a more flexible approach that can enable a continuous transformation towards the next generation of production system based on an evolutionary and iterative procedure, supporting backward and forward iterations [Lo08]. Repeatable process steps are necessary in case the desired conditions are not achieved at first tentative. Thus, *iterative* is the second characteristic expected in a migration process, in order to adapt the migration to any possible change, i.e. system failure, new customer requirements and different environmental conditions.
3. New technology trends and market requirements occur continuously. The migration towards CPPS and, thus, the future industrial revolution, represents a continuous improvement process for the production system. To this end, the

incremental improvement, feature-by-feature and component-by-component, of the system is the third characteristics of the migration, in order to not only minimize the complexity of each implementation step but also to always move towards the system improvement and innovation [SR92] and ensuring increasing added value at each process sequence.

4. In a problem-solving context, according to Ehrlenspiel [Eh07], thinking in *options* is very important as well as generating a variety of possible solutions, which supports the exploration of an option space that can lead to an optimal solution. In fact, the options' thinking is the key to enhance learning and management innovation [BT03]. It is important to take into account that there are different possibilities, in terms of technologies and system solution options, to realize the Smart Factory concept. All these options need to be analyzed to identify how to take advantage moving towards Industry 4.0 at minimum cost and risk. In order to generate and evaluate options within the context of innovative complex manufacturing systems, a migration approach should be also holistic and agile.
5. Usually the selection of the migration target in manufacturing is driven only by costs or technical trends. However the previous section 2.3 highlighted that this selection should be the result of the integrative and interdisciplinary work mode between all technical, operational, organizational, human, and economic functions that need to be considered simultaneously during the decision making process in an *holistic* approach.
6. Within the uncertain and evolving context of Industry 4.0, the migration process should be *agile* to support the continuous refinement of migration plans and goals. Agile methodologies encourage lean thinking to guide the high development of flexible and adaptive systems of high value, understanding that everything is uncertain [NMM05]. Therefore, they are ideal in such projects with highly variable tasks due to volatile requirements, people skills and various technologies used [Hi03] [NMM05].

These characteristics required for a migration process towards cyber-physical production systems are summarized in Figure 2-5 and investigated in the following two chapters.

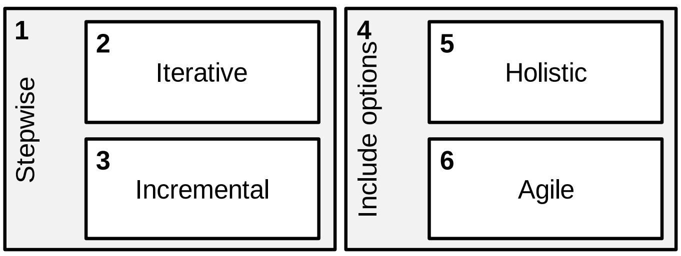


Figure 2-5 Requirements for a migration process towards CPPS

3 Migration in literature

Various approaches towards the migration, i.e. general implementation strategies and migration processes, have evolved over the last decades within past research projects in different domains. In this section the engineering processes and the main migration strategies and processes are analyzed. Strategies and processes are distinguished according to their definition in [Ma96], in which: a *strategy*, or method, consists of techniques for performing a task, while a *process* is a logical sequence of tasks performed to achieve a particular objective [Es08].

3.1 General Migration Strategies

Although legacy system migration is a major research issue in many areas, such as reverse engineering, business reengineering, and data transformation, there are a few comprehensive migration methodologies available. In this section the most common migration strategies used in literature to transform an existing system into a different one are analyzed. Migration strategies can be found in literature under different names although they present similar characteristics, the following sections describe the Big Bang, Parallel Systems, and Phased Introduction migration strategies as the main general approaches [CaP17]. Each approach present advantages and disadvantages, thus only an intensive study on the specific project can identify the most appropriate method to migrate from an existing system to a new one.

3.1.1 Big Bang strategy

Less than a migration strategy, the "Big Bang" can be described as a system transformation in a single operation, in which the legacy system is completely switched off and the target system is switched on in a certain amount of time Δt (Figure 3-1) [Ma14b]. Also referred to as "Cold Turkey" [BS93], "Direct Conversion" [RW18], and "Slam Dunk", this strategy involves the entire redevelopment of a legacy system in order to meet the new requirements [Cr15].

The Big Bang approach requires all systems downtime, all users' disconnection and all forces aligned to the migration in order to complete the transformation to the new system, including the restart of the normal operations, in the minimum time [CaP17].

The success of this approach depends on an intensive preparation phase in which, first, the legacy system is carefully analyzed and, second, the new system is tested several times before being implemented and deployed in order to minimize the risks of failure or compromise the system's quality and performance. This phase is fundamental to guarantee that the new system is ready to be deployed because reverting back to the old system is very challenging and sometimes even not possible at all since the old system is no longer available [HS16]. Contingency plans are, thus, necessary in case the transformation fails. In addition, a migration rehearsal can also prepare the team of operators responsible for the migration process to deal with unpredictable and serious problems that can arise during the system implementation on the real environment.

The Big Bang strategy is usually the only viable migration method when the old and the new systems are incompatible. In any case, it can be advisable if the system is well defined, very stable and small in size. An already planned periodic outage or shutdown of the plant can be the ideal occasion to switch over the old software and hardware systems to the new ones. This strategy can be suitable also in case of migration of production systems requiring a complete technological and organizational change, for example in situations where a new product model is introduced into the system [CaP18].

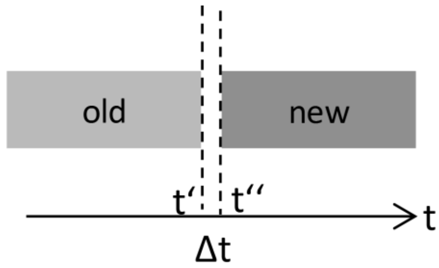


Figure 3-1 Big-Bang strategy [Co11]

3.1.2 Parallel Systems strategy

In the “Parallel Systems” strategy both old and new systems run together for a time period, until the test and validation of the new system are successful and, thus, it is ready to replace the old one (Figure 3-2) [CaP17]. This strategy is also called in literature as “Chicken Little” [BS93] and “Trickle” [Ol98].

Usually, the Parallel Systems strategy consists in implementing the new system incrementally, starting with few applications running in parallel with the current ones. These small applications will replace the old ones as soon as their test results successful and the requirements are satisfied. This process is executed until the new system is fully deployed [AR07].

In general, also the users work on both systems in parallel, so they can understand and learn how to use the new system while still working on the old one. At any time, the migration can be suspended and the new system can be turned off. However, even if running the new system in parallel with the old one provides additional safety and flexibility with lower risks of failure compared to the Big Bang approach, this transformation approach is the least popular since perceived very costly due to the implementation and maintenance of two systems at the same time. Moreover, the duplication of efforts, i.e. operations performed in both systems, increase the complexity and can result in work quality loss.

The Parallel Systems migration strategy can be effective in case of high unconfidence and low maturity of the new technology system, i.e. with low technology readiness level (TRL). Thus, it can be adequate for the migration of critical systems and small production lines that cannot survive with a major system failure [CaP18].

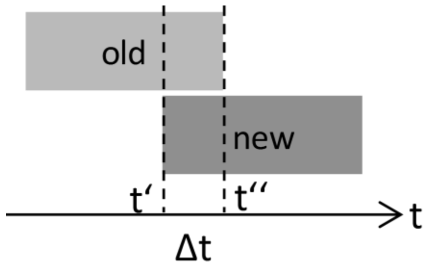


Figure 3-2 Parallel Systems strategy [Co11]

3.1.3 Phased Introduction strategy

The Phased Introduction strategy consists of an incremental and iterative migration of legacy system components into the target system (Figure 3-3). It can be conducted either by introducing the new system first in a specific business unit, moving on area by area, or by implementing different independent modules until the full migration is complete and the new system is used for the whole factory [CaP17]. This strategy is also known as “Butterfly” [Wu97].

The migration is executed through a gradual transition, following a sequence of implementation activities. Initially, a deep study of systems’ interdependencies, priorities and criticalities is required in order to plan the sequence of migration phases in which the target system will be implemented block by block and component by component while replacing the legacy systems. The process is repeated until the target system is fully implemented [CaP18]. Since this process is executed by replacing small blocks step-wisely, it is possible to get feedback between each step going back to the previous step [HS16]. If for some reason a critical problem is detected and something goes wrong, the areas where the new system is deployed can roll back to the old one. The solution will be analyzed again and refined, performing a continuous improvement of the migration.

Usually a phased migration fits well in case of large-scale retrofit. This approach minimizes risk by incrementally narrowing the focus of the migration and, at the same time, provides a contingency position to the old system [CaP17]. To enable the physical coexistence of new and old equipment during the migration process while the plant is in operation, it is important to ensure the communication among systems and easily switch between old and new signals for testing purposes. The execution of a phased migration is obviously longer than the other two but it minimizes risks and results in less downtime [Cr15].

This strategy can be used by large companies, which can build and test a core solution with common functionality and processes before applying it as part of the entire solution. It can be an advantage also for small and medium enterprises that do not have the investment capabilities to implement all the target systems in a single moment time.

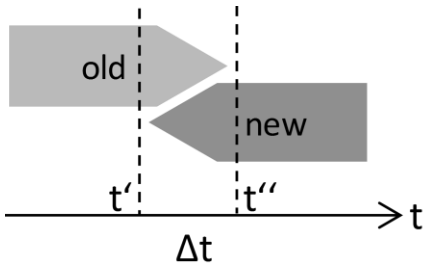


Figure 3-3 Phased Introduction strategy [Co11]

3.1.4 Comparison of strategies and discussion

The described migration strategies are compared in Table 3-1 considering three general key indicators: Cost, Time, and Risk.

Here the Cost indicator does not comprehend the investment on the target system but it considers costs related to the implementation and deployment of the new system, including also the integration and maintenance of legacy systems. Time refers to the migration execution time, thus the length of time taken to completely transform the old system from its current condition into the new system. Finally, the Risk is the probability of failure in the migration to the new system, including losses possibilities in terms of system performance.

	Big Bang	Parallel Systems	Phased Introduction
Cost	LOW	HIGH	MEDIUM
Time	SHORT	MEDIUM	LONG
Risk	HIGH	LOW	MEDIUM

Table 3-1 Comparison of the three migration strategies

This comparison is based on the evaluation provided in [Ma14b], [Cr15], [HS16], which refer to the migration of specific system. Table 3-1 has been also confirmed by the projects use cases experience [CaP17], therefore it can be generalized also to this context.

Big Bang strategy seems simpler compared to the other two migration strategies since it does not need to link the old and the new systems. For example the development of additional interfaces is not required in this case. Notwithstanding the fact that this strategy requires lower implementation costs due to the shorter time frame of the migration, a very high number of issues can occur considering the massive replacement of the old solution with the new one in a single operation. The possibility of risks is related to the system’s performance that can be lower than the old system. As a consequence, also the time for training employees on the new system is shorter.

Conversely, the Parallel Systems strategy is characterized by a low implementation risk, since the new system replaces the old one only when, after a period of parallel running, the requirements satisfaction is proved. This means that in any event there is always at least one system functioning properly. Of course, run and maintain two different systems that perform similar results implicate the highest costs.

The Phased Introduction strategy presents a lower risk of implementation since the new system replaces the old one in small portions at time. Therefore, when a problem occurs, there is more time to resolve it. In fact, the advantage of a phased approach is the possibility to progressively adjust the implementation strategy. Moreover, there is also more time to train employees and the knowledge and experiences gained in initial phases can be used to better implement the next phases. On the other side, its implementation takes longer because of its stepwise and incremental nature and the need to connect old and new systems during the migration period of time.

These three strategies present all advantages and disadvantages but neither strategy is better than the other. The selection of the optimal one depends on the business requirements of the organization itself, the considered environmental context and the addressed technical, economical and social conditions.

Nevertheless, an important aspect to be considered is that different strategies can be combined [CaP18]. Considering for example the implementation of the new system with the Big Bang strategy, everything goes according to plan if new systems are running on the first day and legacy systems do not need to run simultaneously with the new system. But, if the verification test of the new solution does not meet the requirements, the Parallel Systems strategy can be considered as a valid contingency plan.

For this reason, when considering the transformation of an existing production system a hybrid approach, as a combination of the three mentioned strategies, can be more appropriate to guarantee a smooth migration in an uncertain environment [CaP18].

3.2 Engineering Processes

The migration of a production system towards Industry 4.0 is based on the implementation of next generation technologies. To implement engineering changes within an existing production environment a formal plan is necessary. Design engineers need in practice a guideline to select the suitable procedures, methods and tools for each individual design task. Regardless of the selected migration strategy, a migration process that clearly defines the set of activities to be carried out in order to successfully perform the system transformation needs to be outlined.

Indeed, the migration process is a form of engineering process, which is defined in [En41] as a *"sequence of activities of creative application of scientific principles to design or develop structures, machines, apparatus or manufacturing processes with respect to their intended function and economic and safe operation"*.

Existing engineering processes are categorized depending on the point of view but some general patterns are provided, for example, in guidelines like the VDI 2221, 2206, and 3695.

The [VDI 2221] defines an iterative process for product development and design with seven steps. The goal is to perform problem-solving cycles in a system-oriented approach and follow a top-down approach to identify the problems, by decomposing them down to a single-problem, and a bottom-up approach to identify the overall solution starting from solving the single problem.

The [VDI 2206] guides the systems cross-domain design of mechatronic systems. The development of mechatronic systems is characterized by the interdisciplinarity of mechanical and electrical engineering with information technology. The process is based on a general problem-solving cycle on micro level, the V-model on macro level, and on predefined process modules for defined tasks.

The [VDI 3695] aims at supporting engineering organizations in the planning, developing and/or commissioning industrial plants. The process can support different aspects of engineering processes by analyzing the current state of the process, defining planned target states, pre-conditions, and measures to achieve these states. This process directly addresses the use of mechatronic units as engineering artefacts. They are the intended goal of activities within the component business process and are directly exploited within the solution business as input.

Besides the VDI guidelines above there are also dedicated engineering processes for problem-solving and more managerial approaches, such as the "learn and probe" [LaP], the integrated product development [Eh06], and the plan-do-check-act [PDCA].

In general, according to the SIMILAR process [BG97] in Figure 3-4, every engineering process has a similar set of activities that can be generalized as the following: first, a problem is stated on the basis of customer needs. Based on these requirements, alternatives are investigated and the system is modeled. Usually different models of the system are created, describing different components or different views of the system. These models are integrated and the overall system is launched. The last phase is a performance assessment of the system's output. The SIMILAR process is highly iterative since after each phase the outputs of the task performed are re-evaluated against its inputs.

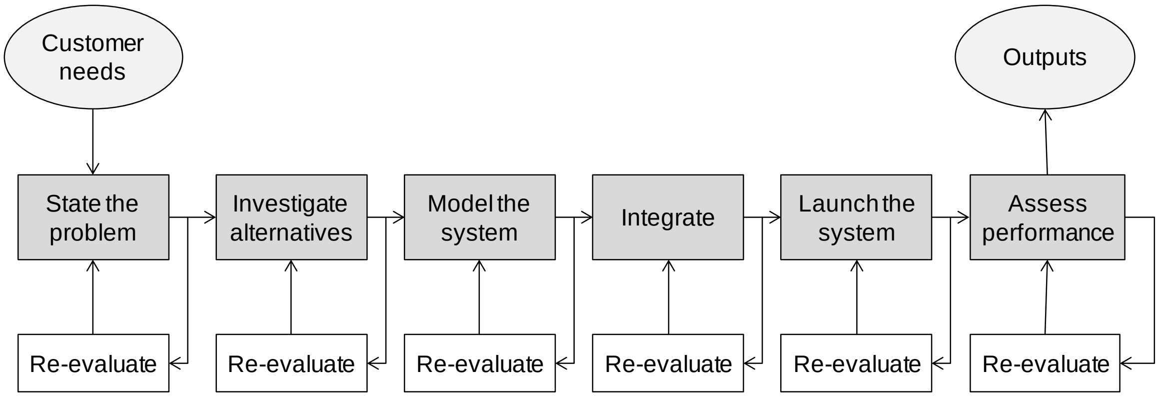


Figure 3-4 SIMILAR process [BG97]

The following section describes some migration processes found in literature that represents new approaches developed on the basis of standard engineering processes and VDI guidelines to define a stepwise migration procedure.

3.3 Existing Migration Processes

Few previous research projects analyzed and developed migration processes to support industries in implementing new technologies. However these processes have not been conceived for planning and supporting a smooth migration towards cyber-physical production systems. A large number of approaches address the migration of legacy information systems and data migration. In addition, some processes and techniques have been defined for migrating from legacy applications to services and cloud computing. The migration processes here collected are addressed to a significant transformation of industrial systems following a stepwise approach.

3.3.1 The Butterfly Methodology

The first model describing a stepwise migration process can be traced back to the 1997. After surveying the processes of legacy information system migration, Bisbal et al. [Bi97] identified five phases for a generic migration process, within the MILESTONE project, from which they specified the “Butterfly Methodology”, i.e. a process that aims at supporting the migration of legacy information systems. The general phases considered are (Figure 3-5): Justification, Legacy System Understanding, Target System Development, Migration, and Testing.

Since the migration of legacy systems carries a high risk of failure, the initial phase investigates risks and benefits associated with legacy system evolution, determining the economic benefits of the transformation. Moreover, the technical feasibility of the target system is analyzed in order to provide an estimation of the possible risks, considering the integration of the new system with other ones and its maintainability. In the second phase the analysis of the legacy systems is fundamental to understand their current functionality and how they meet the requirements, as a pre-condition for the definition of the target system. This includes the identification of the legacy system components, with the analysis of their static and dynamic behavior, and the creation of their design documentation to fully understand the current systems’ characteristics. The main activity in the third phase is the elicitation of requirements and specifications of the target system. In particular, the target system has to guarantee the same functionality of the legacy system and must fulfill the new application requirements. The first aim of the design is to allow further development and evolution of the system architecture, indeed also the selection of the most adequate architecture standards of the target system is very important to facilitate future extensions. Considering the high risk involved in the migration, tests are carried out throughout the evolution process to ensure that the target system meets the required characteristics and functionalities. Several tests are required depending on the nature, size and complexity of the target system environment, such as interfaces with other systems, performance and functionality. Finally, the migration phase consists in the physical transformation of the complete legacy system to the target system that, according to the Butterfly methodology, should be performed incrementally and by small steps.

The Butterfly results in a complex process in which the functionalities of the legacy system are gradually replaced by the target system, aiming at reducing the risk of migration. Naturally, each migration step can be verified and validated with tests, and the legacy system can be rolled back at any stage.

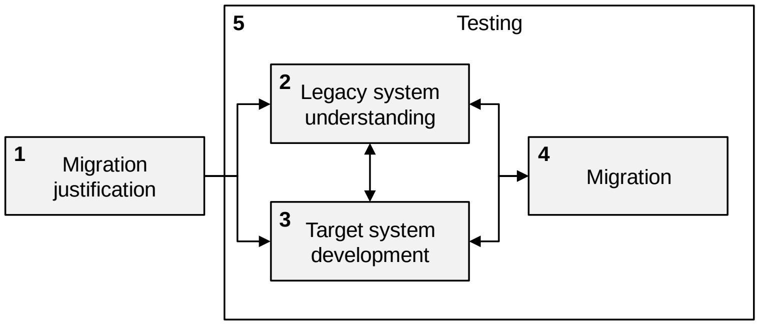


Figure 3-5 The Butterfly migration process

This process provides a more detailed description of the activities to be performed in each phase in case of legacy information systems and data migration. A more general view of the five migration phases, as described above and depicted in Figure 3-5, can be considered as a basis for developing a more specific process.

3.3.2 SMART Migration Planning process

The Service Migration and Reuse Technique (SMART) is an iterative process for migrating legacy IT systems to services in a Service-Oriented Architecture (SOA) environment. As depicted in Figure 3-6, the SMART Migration Planning process has six iterative activities which are: Establish Context, Define Candidate Services, Describe Existing Capability, Describe Target SOA Environment, Analyze the Gap, and Develop Strategy. As stated in Lewis et al. [LeM08], this approach has been developed in 2005 to help the decision-making process of organizations that want to migrate their legacy systems towards SOA by providing them with an approach for analysis of the feasibility, risks and costs involved.

The first task of the process is to understand the migration context in terms of business, stakeholder's goals, candidate services, and legacy systems. Based on the collected information, in the Establish Context phase it will be determined if the migration of the considered legacy systems is feasible or not. Thus, at this stage it is also important to understand the target SOA environment at high level, in terms of technology and components. In particular, the outcomes of this first migration process phase will be the lists of involved stakeholders, migration issues, characteristics, and business process-service mapping. If the legacy system is a good candidate and the migration is considered feasible, the second process phase is gathered and consists of three parallel activities.

In Define Candidate Services, few of the candidate services listed in the initial phase are selected and specified in more details. In Describe Existing Capability, the legacy system components with functionalities that meet the needs of the selected services are described. In Describe Target SOA Environment, information about components, technology and standards of the new system environment are gathered, as well as services implementation guidelines, interactions with the environment and their expected execution quality.

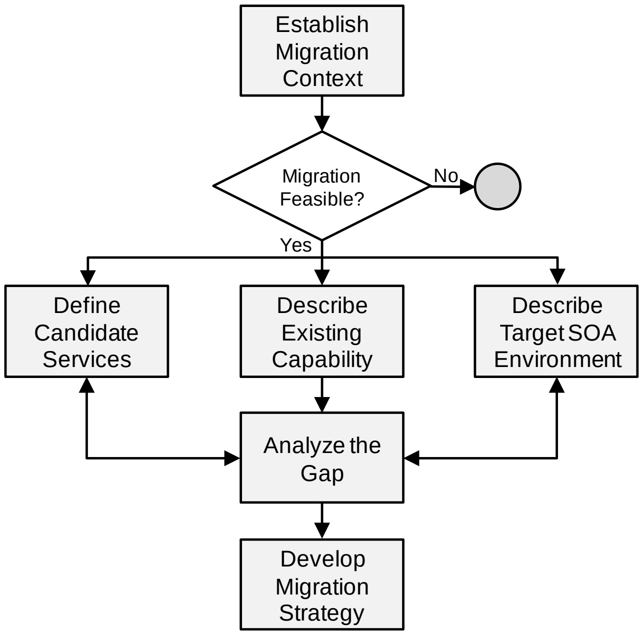


Figure 3-6 SMART Migration Planning process

As soon as all the previous required information are gathered, the Analyze the Gap phase starts with the analysis of the gap between candidate services, target SOA environment and legacy system components to estimate efforts, risks and costs related to the migration. This activity generates issues that need to be considered during the migration and provides the basis for the final process phase Develop Strategy. The migration strategy developed in this last stage takes into account all the characteristics derived from the previous phases, related to the estimation of risks and costs and the migration feasibility. In fact, it includes guidelines for services identification, possible migration paths towards the target architecture and additional information, such as trainings and workshops.

3.3.3 MASHUP process

The MASHUP process (MigrAtion to Service Harmonization compUting Platform) has been proposed by Cetin et al. [Ce07] to migrate legacy software to service-oriented computing. It is based on the mashup technology, which is a hybrid web application that integrates complementary elements from more than one source to create a new single service. The six-step roadmap (Figure 3-7) addresses both the behavioral and architectural aspects of the migration process towards a generic Mashup Server, i.e. a server that contains a service repository and enables the integration of different service sources, called Domain Specific Engines (DSEs) components.

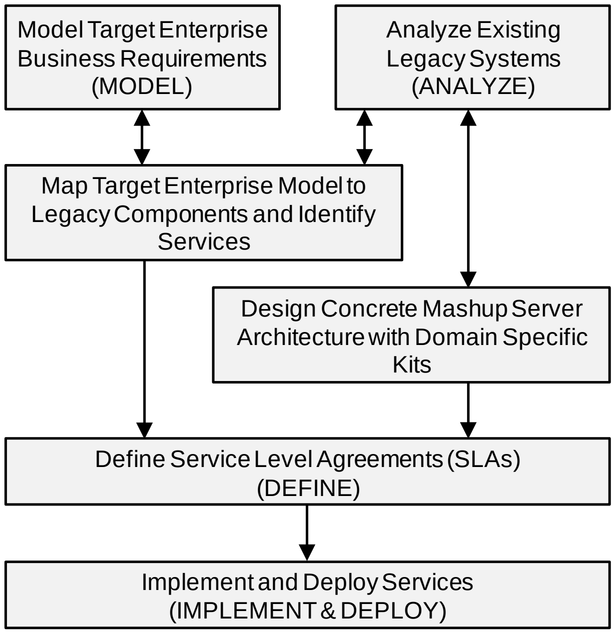


Figure 3-7 MASHUP process

The migration steps are: Model, Analyze, Map and Identify, Design, Define, and Implement and Deploy. In the first step the target business requirements are modeled, using a semantic notation similar to the Business Process Modeling Notation (BPMN), in order to understand the functional requirements of the target system. The Analyze step focuses on the existing legacy systems. The analysis of legacy software helps the identification of important data of the reference architecture, in terms of components, interfaces, quality of service attributes, and level of maintainability and complexity for designing domain specific kits, which are another enabling technology for migration. The Map and Identify step identifies services by iteratively mapping the business, functional and non-functional requirements either into legacy system components or new ones. Within the fourth step a concrete Mashup Server architecture with domain specific kits is designed, moreover the domain specific engines and connectors are identified in the solution domain. The fifth step defines the Service Level Agreements (SLAs), which contains contextual information and the quality of service characteristics, based on the service mapping and the architecture defined in the previous steps. At the final step the system services are implemented and deployed and the legacy components are wrapped and customized for the new architecture.

The described migration process focuses on the specific implementation of service oriented computing based on the mashup technology. Even though it enables the integration of different enterprise legacy applications, the approach can be followed only when the mashup technology is the considered target of the migration.

3.3.4 SOAMIG process model

The SOAMIG Process Model has been developed within the SOAMIG Project, which focuses on the transformation-based conversion towards service-oriented architectures addressing also data, code and user interfaces aspects. The SOAMIG process is defined by Zillmann et al. [Zi11] as a generic, adaptable and iterative migration process model (Figure 3-8) that distinguishes four phases: Preparation, Conceptualization, Migration, and Transition. The Preparation phase focuses first on the preparation of the legacy system code that needs to be renovated. Then it sets-up the project defining the project goals and starts the conversion and reengineering of the tools to be adapted to the project requirements. In the Conceptualization phase the technical feasibility of migration and tool adaptation are assessed in order to define a migration strategy that can iteratively migrate the entire legacy system, which is performed in the Migration phase. During the Conceptualization and Migration phases the seven SOAMIG core disciplines are performed iteratively, which are: Business Modeling, Legacy Analysis, Target Architecture, Strategy Selection, Realization, Testing, and Cut Over. These sequential disciplines use model-driven techniques based on an integrated repository and help to define the iterative tools, services and code migration. Finally, the Transition phase focuses on the evaluation and quality improvement of the migrated system in the target environment.

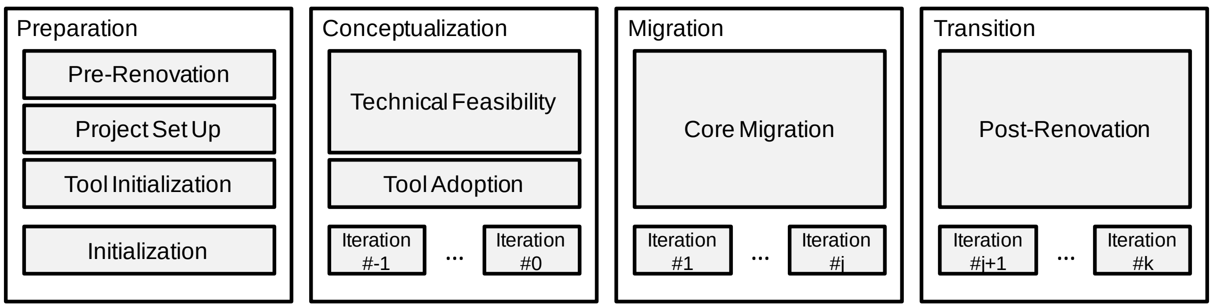


Figure 3-8 SOAMIG migration process

The SOAMIG migration process provides a very detailed description of the disciplines to be performed in each phase, resulting in a well-structured sequence of activities towards the definition of a migration strategy that enables the reuse of legacy tools and code and, thus, implicates low effort and costs. Despite the designated iterations, the process aims at a single solution derived step by step.

3.3.5 Cloudstep process

The Cloudstep decision process supports the migration of legacy applications to the cloud by considering not only the technical feasibility of the target cloud solution but also its impact on the organization. The step-wise process is presented by Baserra et al. in [Be12]. The main objective of the Cloudstep process is the identification and analysis of key factors that might influence the cloud selection and relative migration task.

The process in Figure 3-9 is characterized by nine activities: Define Organization Profile, Evaluate Organizational Constraints, Define Application Profile, Define Cloud Provider Profile, Evaluate Technical and/or Financial Constraints, Address Application Constraints, Change Cloud Provider, Define Migration Strategy and Perform Migration. The starting point is to collect relevant legal or administrative information that might influence the cloud migration decision task. By defining the main organizational characteristics it is possible to anticipate the potential organizational critical factors for the cloud adoption. Consequently, in the second phase, the derived organizational constraints are evaluated and if any critical obstacle is detected the migration process does not proceed. Possible organizational constraints can be the resistance by organizational members to changes related to the migration to the cloud, or data not accessible from outside the organization, and any legal restriction.

The third and fourth phases are performed in parallel and determine the identification of usage and technical characteristics of the application targeted for migration, and the definition of each candidate cloud provider characteristics. Once the application and cloud profiles are defined, the technical and financial constraints are evaluated in the fifth phase. In particular, the evaluation considers seven types of constraints (financial, organizational, security, communication, performance, availability, and suitability) within the same context. The constraints can influence each other and need to be evaluated following a precise priority order.

At this point there are two possible paths in the Cloudstep process. If there are no constraints the next step consists in the definition of the migration strategy, in terms of activities to be performed to accomplish the migration, minimizing migration costs and risks. Otherwise, the next activity addresses the constraints in the context of the application or the constraints due to the cloud provider until no more constraints are identified or the decision to abort the migration process is taken. In case the process continues to the definition of the migration strategy, the actual migration to the cloud is performed moving the legacy application components and data to the target cloud solution.

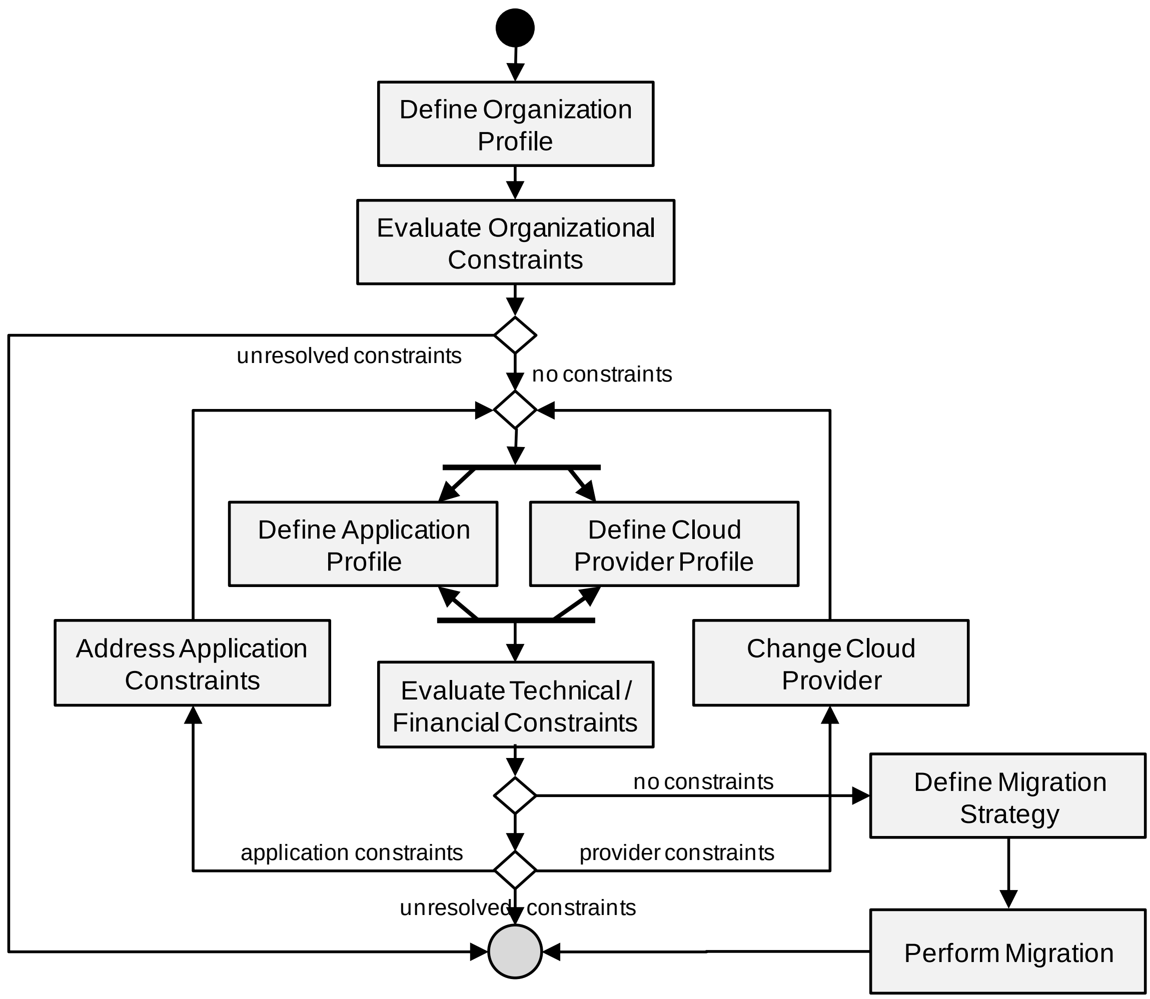


Figure 3-9 Cloudstep workflow

3.3.6 IMC-AESOP Migration process

Within the EU FP7 project IMC-AESOP [Co14a], a stepwise migration process from current SCADA and DCS functionalities, as in the ISA-95 automation pyramid, towards a service-oriented architecture (SOA) has been defined.

The process [De12] considers mainly the integration of legacy systems with the SOA cloud and consists of four main steps (Figure 3-10): Initiation, Configuration, Data processing and Control execution, which enable a gradually upgrading to the target system. The Initiation phase defines the services required to represent the legacy components to the cloud and into the basic architecture, where the legacy subsystems can be migrated. At this stage only parts not highly integrated the legacy DCS/SCADA systems are migrated, such as low level black box and high level systems for business planning and logistics. DCS parts are migrated during the Configuration phase, in which most parts of DCS are engineered and configured in Engineering Stations. The configuration of low-level devices and control is done using the configuration services provided by a Mediator that represents also the configuration aspects of all the legacy systems that have not been migrated yet. The mediator converts the configuration of systems to a format understandable by legacy systems and extracts the configuration of legacy systems if required by the service-oriented architecture. In Data Processing the migration includes all subsystems and components that do not require short response time, with the consequently need to present the large amounts of data available from the legacy DCS to the migrated data processors and other consumers. In the Control Execution phase the legacy SCADA and DCS functionalities are migrated to the SOA.

This migration can be controlled by a detailed schedule of the migration functions with defined deadlines, or by allowing legacy controllers to fade out as functions are migrated during normal plant operations.

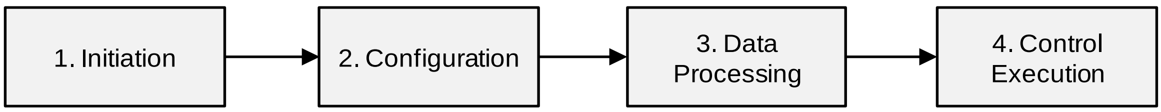


Figure 3-10 IMC-AESOP process

This stepwise migration process has been designed to preserve the system functional integration and real-time control of operations minimizing the system performance risks. However, this process allows only movements directly targeted to the migration end and seems inappropriate for the support of a continuous system migration due to its imposed rigidity and linearity.

3.3.7 XIRUP Modernization methodology

The XIRUP process focuses on the modernization of component-based systems defined in the MOMOCS project. As described by Fuentes-Fernández et al. [FPG12], their proposed model-driven process is based on incremental iterations, in which the new system features are designed and implemented one by one. The XIRUP modernization methodology consists of four-phases: Preliminary Evaluation, Understanding, Building, and Migration, as represented in Figure 3-11.

The goal of the first phase is to decide if the system is going to be modernized or not. To this end, the modernization requirements definition as well as a cost-benefit analysis is conducted. The Preliminary Evaluation phase collects information regarding both legacy system and target platform and analyzes possible alternative features of the solution in order to estimate the modernization activity, with reference to costs, benefits and risks. Based on the analysis results, the proposed modernization can be accepted or not. If the modernization offer is accepted, the second phase, i.e. the Understanding, can take place. Here, the relevant components of the legacy system are identified to understand how the new modernized system can be implemented. Within the Building phase the transformations from legacy systems components to the new system components are established. This phase includes also testing activities to select and validate the transformation models for the system components. Finally, in the Migration phase the transition to the modernized system is carried out. The activities involved in this last phase consist in the detailed design of the transformation models of new components and, then, their deployment and configuration with the legacy system.

The particularity of the XIRUP process model is that it considers always an evaluation activity at the end of each phase, as depicted by the arrows in Figure 3-11, enabling a continuous and incremental improvement of the considered system.

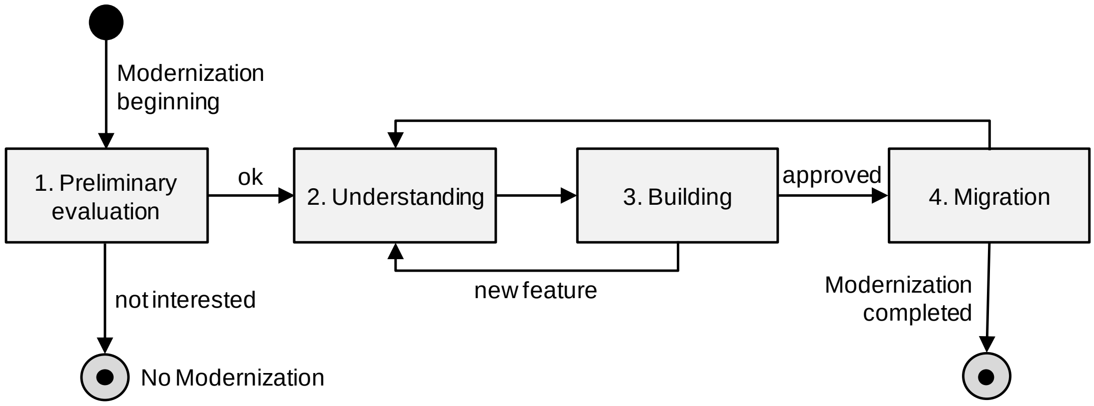


Figure 3-11 XIRUP process model

3.3.8 Synthesis and Derived Gaps

Some conclusions can be derived from the small set of recent migration approaches illustrated in this chapter. As represented in

Table 3-2, regardless of domain and target of the migration, the described processes present some similarities and differences:

- All the processes are stepwise: they analyze first the current systems and the target solution, then they develop the target solution, and finally the migration, i.e. the target solution implementation, is defined and performed.
- The requirements of the target solution are usually defined during the first phases. While SOAMIG and IMC-AESOP focus mainly on the technical constraints and characteristics of the migration, processes like SMART, MASHUP and XIRUP analyze also business requirements and stakeholders' needs. Cloudstep investigates also legal, administrative and organizational constraints.
- Mostly of the described processes define the migration in an iterative approach but only XIRUP takes into account possible new features after the successful validation of the migrated components. Migration processes usually support the

system transformation to a precise goal (e.g., service-oriented architecture, cloud computing) rather than considering a continuous improvement from a system view towards the technology innovation.

- Moreover, these processes typically define the migration strategy to the target system not taking into account other possible alternatives of migration and their evaluation under technical, operational and human aspects.

Table 3-2 compares the described existing migration processes with the derived characteristics of a migration process towards CPPS. Among the processes described in this chapter, the XIRUP modernization process is the one that matches the most characteristics derived in Chapter 2.4. However it does not comprehend a phase in which alternative solutions are investigated before defining the system. In addition, it evaluates in the preliminary phase only technical characteristics of the system and business requirements, neglecting other important aspects of a system, such as operational and human.

	Butterfly	SMART	MASH-UP	SOAMIG	Cloudstep	IMC-AESOP	XIRUP
Stepwise	●	●	●	●	●	●	●
Iterative	●	●	◐	●	●		●
Incremental			●	●	●	●	●
Include Options		●		●			
Holistic		◐	◐		●		◐
Agile							●

Legend: ● fully matched; ◐ partially matched

Table 3-2 Comparison of existing migration processes

Contrarily to the existing processes, the migration process should consider all the characteristics defined in Chapter 2.4 in order to enable the migration. Therefore, a new migration process, suitable for CPPS, needs to be defined.

The migration process towards CPPS should be stepwise, like the current processes, but also iterative and incremental to ensure a smooth but progressive migration of the system. Some of the stepwise migration processes analyzed in this chapter are either iterative or incremental. Only SOAMIG, Cloudstep and XIRUP present both characteristics.

The definition of process stages, dedicated to specific tasks, helps the users to clearly distinguish the different tasks to be performed, focusing on one activity at time. The iteration is then important to guarantee the continuity of the process, ensuring that the output of each phase is still valid in accordance to the input/output of the previous phases. Moreover, each following phase should lead to a refinement, with greater details, of the migration solution specification.

To ensure the identification of the optimal migration solution for a factory, the migration process should include in its phases the evaluation of alternative options. Moreover, since the migration towards CPPS particularly address not only the technologies of the shop floor but also its ecosystem, the solution alternatives should be generated from the analysis of their impact on different levels, such as economical, operational and social.

None of the existing migration processes derive solution alternatives from the analysis of different factory dimensions. Some processes evaluate technical and business requirements but do not consider them to generate options and define a solution space.

Finally, the process should be agile in order to allow also a kind of flexibility to modify the migration approach according to changing conditions of the market environment or even the system goal. This characteristic, particularly important in the context of Industry 4.0, is missing in all migration processes described but XIRUP.

4 Related engineering practices

Since the digital transformation and adoption of the next generation of smart technologies has no clear industry-wide approach, the migration towards the Industry 4.0 vision is challenging. The implementation of CPPS technologies on existing heterogeneous production environments will have a big impact on the entire factory. This change has to be managed with structured methods in order to ensure the evolutionary improvement of the factory as result of the deployment of new technologies.

This chapter investigates some system development techniques in engineering dealing with decision-making processes to support the transformation process from the third to the fourth industrial revolution in manufacturing when the target condition and the way forward are unclear and uncertain.

The first section introduces routines usually applied within manufacturing organizations to incrementally improve and optimize systems: the lean and agile methodologies. The second section describes the maturity models as means to provide a description of evolution paths. The third section presents the system modeling techniques as depiction of system evolution.

These strategic techniques could fulfill the last three requirements of a migration approach towards the Industry 4.0 paradigm: include options, holistic, and agile.

4.1 Lean and Agile methodologies

The derived transformation's characteristics in Chapter 2.4 are very close to the Lean and Agile principles, although they are not correlated in nature. Next sections briefly describe the fundamentals of both approaches and how they can be applied to the migration strategy towards Cyber-Physical Production Systems.

4.1.1 Lean manufacturing approach

Lean manufacturing, originated in Japan after the Second World War to cope with low cashes and few industrial resources, is often correlated to the Just-in-Time manufacturing or Toyota Production System (TPS) [GMC14]. In general, the lean approach promotes driving waste out of the manufacturing cycle. i.e. defects that require unnecessary rework and processing steps. Toyota's definition of waste includes *muda*, *muri*, and *mura*.

Muda means "waste". In the TPS eliminating waste is the key to efficiency. The types of waste are seven: transportation, waiting, motion, over-processing, inventory, over-production, and defects. *Muri* means "overburden". Overburden of equipment and people can be avoided through standardized work and distributed production workload in standard processes. *Mura* means “unevenness”, which can be avoided through the Just-in-Time principles aimed at reducing time fluctuations of production operations by using the first-in first-out (FIFO) flow [Oh88].

To create an ideal lean manufacturing system, three steps have been defined in [Pa04]:

1. Design a simple manufacturing system
2. Recognize that there is always room for improvement
3. Continuously improve the lean manufacturing design

Lean also concerns the integration of humans in the manufacturing process through continuous improvements [MW17], in which repetitive operation should be performed by machines while creative and thinking activities should be done by humans.

Although lean manufacturing focuses on the elimination of waste at operational level, it has evolved to the strategic level concept of lean thinking, which focuses on the identification of value and generation of flow of value to the customer [Me05]. In particular, lean thinking promotes continuous improvement towards “perfection” [HHR04].

4.1.2 Agile development methodology

Agile methods have been created as practices for software development. In particular, planning, design, development, and testing are integrated into an iterative lifecycle to deliver software at regular intervals [Ma02]. The goal is to follow a continuous improvement cycle (Figure 4-1), exposing flaws faster and reducing waste. The advantage of agile development is a faster achievement of value as software releases arrive to customer more frequently.

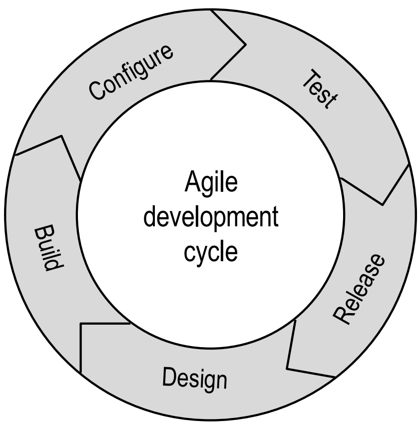


Figure 4-1 Agile development process

More in general, the groundwork of agile methodology is in the time-focused, iterative and incremental development [Ka13]. Repeated iterations can effectively control the progress, reduce risks and react to changes or failures more quickly than traditional

Waterfall approaches, which do not allow for mid-course corrections [CMM15]. In other words, “Agile development” consists in evolving the product trough incremental small steps, instead of “all-at-once”, leading to feedback that allows requirements to be tested and adjusted at any step. Being “Agile” means very flexible and able to quickly adapt to changes, enabling also a fast decision-making process.

A large number of agile methods and tools have been introduced recently, all following the same philosophy and, thus, the main rules defined by the Agile Manifesto in 2001 [Be01]:

- *Individuals and interactions over processes and tools*
- *Working software over comprehensive documentation*
- *Customer collaboration over contract negotiation*
- *Responding to change over following a plan*

With these values, the Agile Movement emphasizes first the team relationships in contrast to development processes and tools. Second, it values working software more than spending too much time on documenting the product for development. Third, it considers the customer as a collaborator throughout the development process making. Fourth, it always views changes as project improvements that provide additional value.

4.1.3 Lean and Agile for migration strategy: the Toyota Kata

Lean and Agile approaches are different. They both take Just-in-Time action but they support different things. While the Agile methods focus on the product evolution supporting creativity, learning and innovation, the Lean continuous improvement refers to the process being used and supports optimization through analysis, waste reduction and control [Ma12].

Within the context of Industry 4.0, which deals with complexity and improving productivity, Lean or Agile alone are not sufficient to address the current manufacturers’ operational challenges. However, a balanced combination of the two approaches can support the complex definition of migration strategies towards CPPS when both what is needed and how to get there are not obvious [St10]. When the desired target (TO-BE) situation and even the way to get there are unclear, an iterative approach is very important to clarify both the “what” and “how” and to handle uncertainty [LL08] step by step. In fact, a step-wise approach enables production environment to gain quick benefits, identifying and prioritizing requirements and needs for improvement, and make production ready for future scenarios towards Industry 4.0. To enable Industry 4.0 scenarios, firstly concrete problems should be eliminated, while future scenarios will bring to light other new aspects that need to be analyzed carefully [KT16b].

This decision making process, as shown in Figure 4-2, can identify, analyze and solve one problem at time but always providing an added value at each iteration while considering new and changed input factors or priorities.

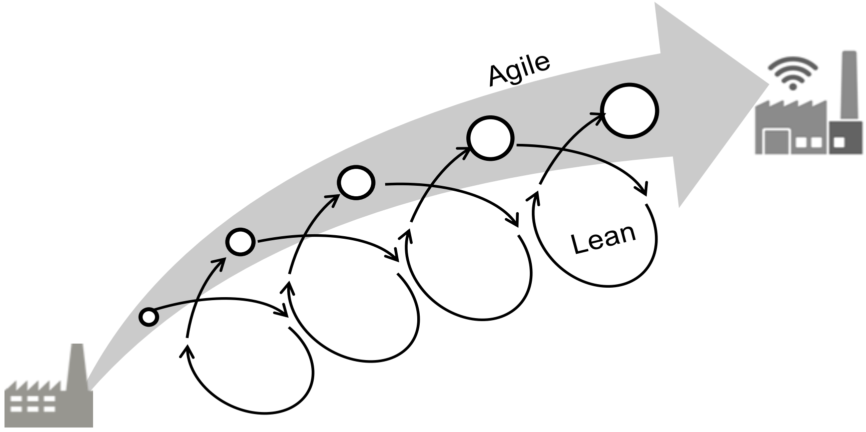


Figure 4-2 Decision-making approach based on Lean and Agile thinking

An approach that promotes this kind of decision-making process is the Toyota's Improvement Kata [Ro10] – a structured and iterative approach designed for continuous improvement of any industrial process dealing with uncertainty, i.e. obstacles, complexity and unclear territory. The Improvement Kata describes a routine to achieve goals within an organization by defining four iterative steps towards a defined target condition (Figure 4-3), as reported in [Ro10]:

1. *In consideration of the overarching direction or challenge…*
2. *Grasp the current condition,*
3. *Define the next target condition,*
4. *Move toward that target condition iteratively via experiments, which uncover the obstacles that need to be worked on.*

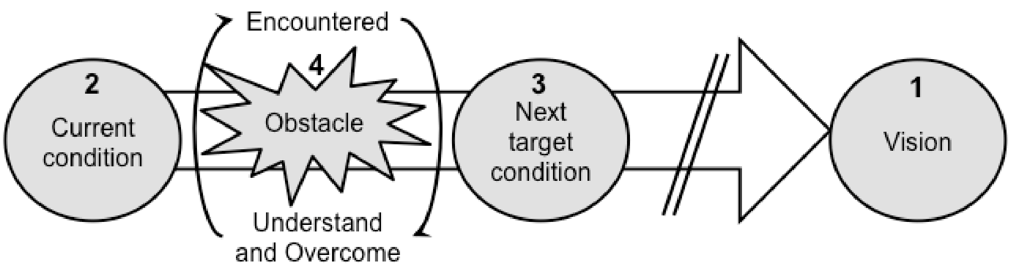


Figure 4-3 The Improvement Kata Pattern [Ro10]

Basically, it consists in defining a target condition at a time as a partly realization of the long-term vision or challenge based on the current condition. Once the target condition is defined, a series of Plan-Do-Check-Act (PDCA) cycles [MN06] towards that condition begins. At every achievement of the target condition, the four steps of the Improvement Kata are repeated until the long-term vision is reached. These four-step routines define a way of thinking and acting, tailored for changing, improving, and learning, which can be adopted to the migration process towards cyber-physical production systems.

4.2 Maturity models

According to Maier et al. [MMC12] the term “maturity” *implies an evolutionary progress from an initial to a desired or normally occurring end stage*. The “stage” refers to the stage of growth [No79] in the evolution of data processing, in which the last stage represents the reached “maturity”. Following this perspective, the maturity model constitutes a tool to assess in which stage of growth a system is, assuming that it evolves automatically over the time, passing all the stages due to improvements effects.

In 1979 Crosby [Cr79] proposed a maturity grid for quality management process that clusters best practices across five maturity stages and six measurement dimensions.

Although Nolan proposed an evolutionary model that sees the stages of maturity as steps through which every system will improve, Crosby introduced the evolutionist model that considers the maturity as a series of steps towards progressively more complex and perfected version of the current status of a system.

In literature there is not a general and clear classification of maturity models because of the different interpretation of the maturity concept adopted by evolutionist or evolutionary models. Only Fraser et al. [FMG02] distinguished three typologies of maturity models that are: Maturity grids, Likert-like questionnaires, and CMM-like models.

The maturity grid represents maturity levels in a simple and textual way and is structured in a matrix, or grid. Its main characteristic is that it does not specify the particular process. However it highlights the characteristics any process should have in order to enable enterprises in achieving high performance. Maturity grids only identifies some characteristics that any process and every enterprise should have in order to reach high performance processes [Ri17].

The questions of a Likert-like questionnaire are basically statements of good practice, while their answers, related to the considered enterprise performance, are rated on a scale from 1 to n [Ri17]. Likert-like questionnaires can be defined hybrid models, since they combine the questionnaires approach with the definition of maturity. Usually, they have only a description of each level, without specifying the different activities that have to be performed to achieve a precise maturity level.

Finally, there is the CMM (Capability maturity model), which presents a more formal and complex architecture compared to the previous ones. The CMMs consist of process areas clustered according to their common characteristics that, thus, specify a set of practices or activities related to a succession of goals. Typically, the CMMs exploit Likert questionnaires to assess the maturity [Ri17]. An improved version of these models is represented by the Capability Maturity Model Integration (CMMI) [CM02]. The CMM has been applied in different process areas specifying where an organization should focus to improve processes and deriving a set of related activities, which achieve those goals considered important for improving process capability. Therefore, each process area is described with key practices that define the activities and infrastructures necessary to enable the required process improvement.

The overall goal of maturity models is to represent the current maturity situation of an organization and to provide guidelines on how to achieve a higher maturity level.

In general, they can be applied for different purposes [DCa17]:

- Descriptive, to represent the assessment of the AS-IS situation of a company;
- Prescriptive, to indicate how to improve its maturity in order to result in a positive business value;
- Comparative, to enable benchmarking across companies and recognize the maturity level among similar business units.

In general, as stated by [We12], CMMI-based models provide an objective and generalizable assessment method, with no specific best practices. Therefore, they can be easily applied to different industrial domains and used only as base to derive appropriate transformation paths towards an industry specific scope.

4.2.1 Industry 4.0 maturity models

In the recent years some authors proposed maturity and readiness models and assessment surveys within the context of Industry 4.0. Most of these existing capability maturity models have 5 maturity levels and a various number of dimensions related to smart products and services, smart processes, and strategy and organization. These models can be considered as tools meant to embrace significant growth opportunities by digitally transforming companies' business and, at the same time, identifying where improvement is needed and where investment is required.

Table 4-1 compares the four most-known Industry 4.0 maturity models with descriptive, prescriptive and comparative purposes. Similar maturity models can be found in [Ke13], [AUC18], and [GȘE17].

The Industry 4.0 maturity models listed in Table 4-1 are particularly well structured and provide a good overview and also defined details about their assessment methodology.

However they present numerous dimensions, which cannot be easily linked to each other in order to provide also a clear correlation among them.

Nevertheless, these existing maturity models provide a good basis for an extended and redefined specific maturity model related the migration towards cyber-physical production systems, focusing especially on technical, operational and human aspects.

Name	Levels	Dimensions
"Industrie 4.0 Readiness" – IMPULS [Li15]	5	*Strategy and organization, Smart factory, Smart operations, Smart product, Data-driven services, and Employees.*
"Industry 4.0 Maturity Model" [SES16]	5	*Strategy, Leadership, Customers, Products, Operations, Culture, People, Governance, and Technology.*
"Industrie 4.0 Maturity Index" – acatech [Sc17]	6	*Resources, Information systems, Organizational structure, and Culture.*
"Digital Readiness Maturity Model" (DREAMY) [DCa17]	5	*Design and Engineering, Production Management, Quality Management, Maintenance Management, and Logistic Management.*

Table 4-1 Comparison of the most-known Industry 4.0 maturity models

4.3 Systems modeling techniques

According to the Industry 4.0 vision, the main characteristics of a Cyber-Physical Production System are smartness, flexibility and adaptability to dynamic market changes. Such a complex system consists of a large number of components that are all integrated together and need to operate as a single entity. Mastering the complexity of such innovative systems is a challenging goal because of the number of functions, components and interfaces. Therefore, since decades the technique of abstraction has been used by engineers to deal with complexity and make problems easier to understand and solve [Ba11].

As manufacturing systems are becoming more and more complex with the advent of Industry 4.0 solutions, it is very important to identify modeling techniques for them in order to manage their complexity and interoperability within a complex environment of integrated heterogeneous components [VC18]. Modeling is a universal technique for system representation to understand and simplify the reality through abstraction, i.e. computer-aided design (CAD) technology is used since 1960s to design tools, machinery, products and also buildings or industrial structures.

Since few years the Systems Engineering (SE) emerged with its methodologies to handle high complex systems from a multidisciplinary engineering perspective. Instead of concentrating on the details of individual aspects of a system, like the other engineering disciplines, the Systems Engineering is concerned with the integration of multiple specific aspects into a coherent and effective system. The increasing complexity of systems demands a more rigorous and formalized systems engineering practices. To this end, Systems Engineering promotes the transition from a document-based to a model-based approach to describe a system.

As defined by [FAA06]. "*Systems Engineering is a discipline that concentrates on the design and application of the whole system as distinct from the parts. It involves looking at a problem in its entirety, taking into account all the facets and all the variables and relating the social to the technical aspect*". Also, the system is defined in [ISO/IEC/IEEE 15288] as "*an integrated set of elements, subsystems, or assemblies that accomplish a defined objective*".

The SE is possible only through four main enablers: methodology, process, language, and people [BCF18]. These enablers are described in the following sections.

4.3.1 Model-Based Systems Engineering and the V-Model

The Model-Based Systems Engineering (MBSE) has been defined by INCOSE [IN15] as a formalized model-based approach to model system requirements, design, analysis, verification and validation activities in all phases of a system life-cycle.

The MBSE allows managing complexity by providing modeling techniques, which analyze requirements, structure and behavior of a system. MBSE leads to the specifications of the system through a structured set of digital models that represent its operational, functional and physical description also at various levels of details granularity, i.e. from the system of systems to the elementary component level. Moreover, these models can be easily shared within a community of users and easily stored by a data management system. Thus, the benefits of graphical modeling of the system are numerous, namely enhanced communication, reduced development risk, improved quality and enhanced knowledge transfer.

The overall goal is not only to provide a starting point for the domain-specific system development, but also to act as a common information exchange layer for the involved disciplines throughout the whole engineering process. Especially early analysis of the integrated system model offers high potentials to realize a leaner development process.

Methodologies for system modeling are various. Usually the modeling activity consists in the analysis of the system functionality, i.e. allocating system's requirements by means of functional modeling and then predicting the performance of the system by means of physical modeling [BCF18]. The physical modeling is based on some mathematical description of the system behavior, while the functional modeling is supported by specific language and tools only since few years.

In most cases the design process of MBSE methodologies is based on an iterative flow of activities described by the V-model of systems engineering [IN15]. The V-model (Figure 4-4) is a sequential process that describes the core activities of systems engineering during the life-cycle stages. Development time and maturity move from the left to the right across the diagram, from the stakeholders' requirements identification to the definition of a system concept to the design of system components and the validation of the final system. Particularly important in this process is the backward arrow, which indicates the iteration of the process at each stage to ensure the feasibility of the system concept according to the stakeholders' requirements.

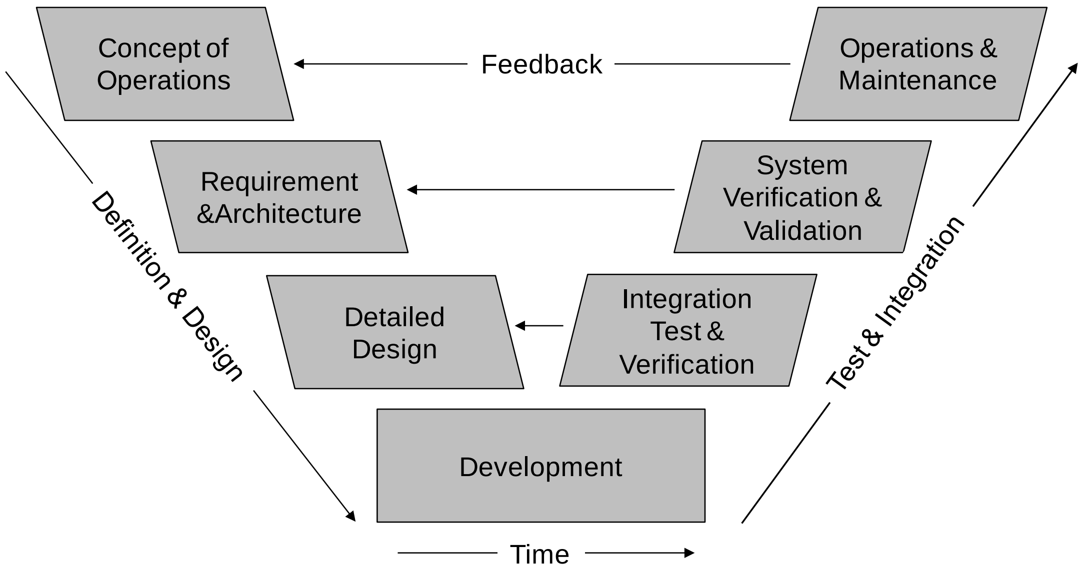


Figure 4-4 V-Model [VDI 2206]

4.3.2 Systems Thinking and Systems Modeling Languages

Systems engineering is a people business. Dealing with complex systems means often involving different disciplines and technical competencies. Systems engineers need adequate skills to design and manage a complex system over the life cycle. The most important skill is the "system thinking", i.e. *think and act in a "system way"* [La10]. The system thinking approach helps engineers to solve problems understanding the context and its relationship with other entities, having thus a holistic view on the complete problem during all the stages of the system lifecycle [Be13].

Systems engineers apply integrated engineering techniques from different disciplines to the engineering of systems. Therefore, they also need to share project's information with everyone on the team to keep the project on track. Systems engineers collaborate in heterogeneous environment and apply systems thinking during the development of complex systems with the support of specific MBSE tools and languages [BCF18]. A common foundation for modeling a system, with an established common language, is the best way to overcome communication difficulties in a large and heterogeneous team environment.

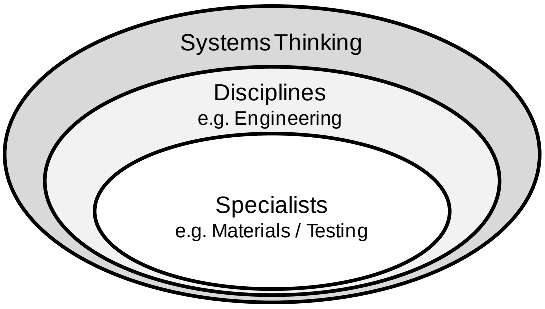


Figure 4-5 Systems Thinking

Indeed, to model a system it is necessary to use a common language easily understandable by all the involved engineers and other users. Therefore, a fairly intuitive language based on a standard set of symbols and items should be used.

Systems engineers have developed graphical modeling languages for years and various versions are available, such as the Unified Modeling Language (UML), the System Modeling Language (SysML), and the Business Process Modeling Language (BPML).

Other languages have been later developed on the basis of UML and SysML that are explicit defined for specific domain or modeling activities, like the Domain Specific Language (DSL), the Interdisciplinary Modeling Language (IML), or the Lifecycle Modeling Language (LML).

Reports on system modeling languages surveys can be found in [KH09] and [Si15]. Recently other languages have been developed for modeling automation and digital systems, such as the SysML4Mechatronics [KV13].

All these languages provide a valuable mean to model a complex system, textually or semi-graphically. This thesis refers to the most commonly used language in Model-Based Systems Engineering: SysML. The System Modeling Language (SysML) has been developed by OMG and is a general-purpose graphical language based on the standard software language: the Unified Modeling Language (UML), version 2. SysML provides means to capture the system modeling information as part of a MBSE approach without imposing a specific method on how this is performed. By means of diagrams, developed to represent and analyze the system from different points of view, SysML supports the definition of system requirements and system specification, as well as the design of the system structure and behavior [BCF18].

Four main typologies of diagrams can be distinguished within the SysML (Figure 4-6) [FMS14]. *Requirements diagrams* allow the visual and graphical representation of textual requirements to integrate and allocate them to system functions or components, *Behavior diagrams* are used to model the system behavior emphasizing inputs and outputs to define functions and goals through a sequence of actions and operating conditions, *Structure diagrams* describe the architecture of the system by defining every entity as a *block* and representing the interfaces and correlation among them, and *Parametric diagrams* are used to model some constraints that affect the value properties of blocks.

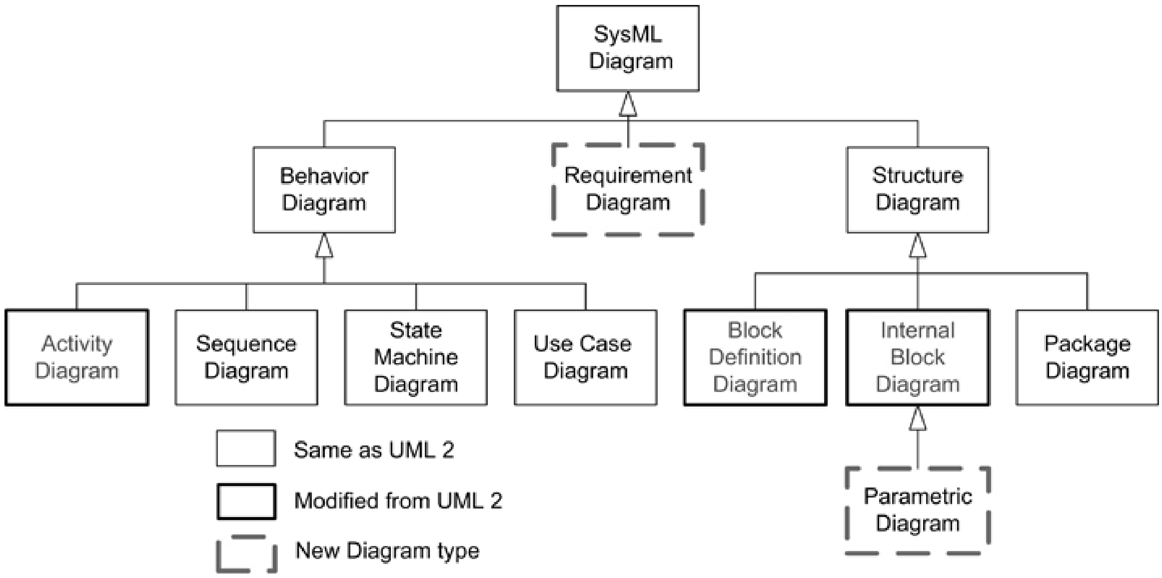


Figure 4-6 SysML diagram taxonomy [FMS14]

The implementation of MBSE requires the support of software tools that enhance the efficiency of the process tasks. One of the most used tools for requirements elicitation is the IBM Rational DOORS, usually integrated with the IBM Rational Rhapsody for system modeling. Other well-known tools are Enterprise Architect (Sparx Systems), MagicDraw (No Magic), PTC Integrity Modeler, and also some open source tools like Modelio (Modeliosoft) and Papyrus (Eclipse). These supporting tools offer different contents, in terms of options, modules and features according to the different MBSE methodologies [BCF18].

5 Research Needs

The fourth industrial revolution will happen inevitably. Industries need to migrate towards the new paradigm of Smart Factory of the Industry 4.0 in order to stay competitive in the market. To this end, several smart technologies, intelligent systems and innovative solutions have been developed in the past years to enable the realization of “digitalization”. However, the introduction of these new technologies in existing production systems is always very difficult. Manufacturers, in order to accomplish their goal of “digitalization”, need to be supported with established methodologies to migrate towards CPPS.

Current migration strategies and processes cannot be applied to manufacturing transformation towards Industry 4.0 because they focus on particular solutions neglecting other related technological and organizational issues. The existing engineering process do not support the definition of a migration strategy towards cyber-physical production systems, while the migration strategies and processes do not help in the minimization of risks related to the implementation of non well-known solutions such as CPS, intelligent devices, and other smart applications, within legacy production systems.

The change is going to impact industries at all dimensions, ranging from technical to operational, human and business aspects. Engineering techniques for change management at company level are various, but still they have not been developed with the purpose to rapidly migrate to the next industrial revolution. Other practices, such as available digital maturity models, focus on the definition of roadmaps to Industry 4.0 but addressing only the technology maturity of a factory, neglecting the impact of each of these innovative technologies on the organization or business strategy.

The combination of existing processes with the concepts described in Chapter 4 of lean and agile, maturity model and model-based systems engineering can contribute to derive a holistic migration strategy towards cyber-physical production systems. In particular, lean and agile approaches support the stepwise and continuous improvement and innovation of a system towards a defined goal. Maturity models support the definition of these migration steps taking into account different system’s perspectives. Finally, the model-based systems engineering approach provides a methodology and tools to holistically represent the system and its changes during the migration process.

Until now, an approach that integrates all these aspects that can support systems migration towards Industry 4.0, minimizing the risk related to the implementation of smart and intelligent solutions, is still missing. Existing migration approaches consist of a stepwise process of system changeover with low risks, since every change does not affect other systems or the system architecture, and in accordance with investments ability of the plant operator. However, to deploy decentralized and smart automation system in industrial environment, not only assets and processes need to be improved but also the IT control system architecture to enable the network of CPS. Therefore, the migration strategy must consider different aspects of the transformation because only the integration of assets, processes and IT systems will improve the whole value adding process.

Therefore, the goal of this research is to understand how to move from “automation” towards “digitalization” in order to enable the envisioned fourth industrial revolution. As stated in Chapter 1 the main research question in this study is:

How to derive migration strategies towards Cyber-Physical Production Systems?

Namely, how the factories of the “automation” era can migrate towards the Industry 4.0 paradigm without being disrupted and maintaining their competitiveness into the market.

For answering the main research question, three sub-research questions are defined below in details.

RQ1: *What approach can mitigate the introduction of digitalization and robotization in manufacturing domain?*

The migration towards CPPS is a complex and overwhelming task. A general approach to derive migration strategies to support migration needs to be carefully investigated, according to the specific factory conditions and goals. Available migration approaches presented in Chapter 3 are based on a technical goal rather than a change in the business strategy. To close the gap identified in Chapter 3.3.8, other engineering practices related to system development and improvement have been considered, although they are not targeted to the Industry 4.0 paradigm.

The proposed migration approach embeds lean and agile philosophies to derive migration paths leading to the system optimization by implementing Industry 4.0 technologies, which are often unclear and uncertain for manufacturers that intend to preserve their legacy production systems and their investments.

This question is answered in Chapter 6.2, which defines the logic behind the definition of the optimal migration strategy for existing production systems in order to keep pace in the evolving context of the fourth industrial revolution.

RQ2: *What process can support manufacturers to migrate towards Cyber-Physical Production Systems?*

The general approach is not enough; manufacturers need also a step-by-step procedure to define their migration strategy, as well as methods and tools to accomplish each task of the procedure. In Chapter 3.2 a set of existing migration processes has been presented showing that previous work on migration processes has focused mainly on the straight implementation of new informatics solutions. Since these processes cannot be considered as a valid support for manufacturers to migrate their production systems towards CPPS, this question aims at defining a process able to identify optimal Industry 4.0 solutions according to the manufacturers' needs.

This question is answered in Chapter 6.3, which describes a general 5-phase migration process towards CPPS aiming at supporting the identification, definition and implementation of each migration step in the perspective of an incremental and continuous innovation improvement of a system.

RQ3: *What methods and tools can enhance the investigation of different migration alternatives?*

The alternative migration solutions can be numerous depending on the actual options in terms of existing technologies and company's constraints. Thereby, the migration process requires additional methods and tools to support the identification, evaluation and selection of alternative migration solutions based on Maturity Models and the discipline of Model-Based Systems Engineering.

This question is answered in Chapter 6.4, which presents three adequate methods and tools supporting the investigation of different possible migration paths according to the definition of the long-term vision and the short-term goals.

Finally, the migration approach, process and tools are applied to a real industrial use case in Chapter 7.

6 Holistic Migration Approach towards CPPS

Following the requirements derived in Chapter 2.4, a corresponding approach is developed within the following chapters leading to the holistic migration approach towards CPPS (HoMoCPPS). Chapter 6.1 defines the baseline for the development of an approach that supports manufacturers in identifying the optimal migration path towards the unclear and uncertain revolution of “digitalization”. Chapter 6.2 presents the logic of the migration path definition, while the HoMoCPPS process is described in details in Chapter 6.3 and substantiated with methods and tools in Chapter 6.4.

6.1 Founding Principles

This chapter provides an overview of those principles that build the foundation of HoMoCPPS. Three fundamental aspects have been derived from the literature research, reported in chapters 3 and 4, which support the definition of a migration strategy for industries aiming at transforming their traditional production systems in the CPPS envisioned by the Industry 4.0 paradigm in order to stay competitive in the market. The first aspect is the support for continuous improvement in such an evolving industrial revolution; the second aspect is the need for options investigation approaches to handle numerous and uncertain solutions; and the third aspect is the multi-disciplinary approach to holistically analyze the impact of the new technologies at different dimensions of the factory.

6.1.1 Continuous Improvement

The migration towards Industry 4.0 is not a one-time operation, but rather a continuous one. Today Industry 4.0 cannot be considered as something that will only be available at some point in the future but rather as a continuous and innovative development of existing technologies and solutions. As manufacturing companies experience increasing competition in the global economy and shorter innovation cycle, it is vital to seek continuous improvement methods to be ready to adapt continuously to changing market conditions at a faster pace than rival organizations and manage uncertainty.

However, the decision to change and improve the production system into a CPPS is very challenging when the way forwards, the target conditions and the possible technologies solutions to be implemented are unclear and uncertain. Sometime the consequential benefits of new technologies on the production system can only be assumed. To mitigate risks related to the implementation of non well-known solutions, system changes should be done as constant small incremental improvements (kaizen) to redefine business in certain areas.

Therefore, the migration towards Industry 4.0 requires a systematic approach to innovation with a continuous improvement mind-set [Ro10] that focuses on appropriate change strategies on culture of Lean thinking, continuous improvement and articulated incremental change over short time-scales to gradually extend the scope. In addition, a roadmap approach has to be defined to help practitioners understand how and when apply specific methods and tools to stabilize the changes on the entire production system.

The PDCA (Plan-Do-Check-Act) cycle [MN06] in Figure 6-1 is one of the most known processes to manage uncertainty in innovation change projects, in which a small change is usually planned based on assumptions or hypotheses but is then deployed only after experimental tests and evaluations of the results. When the change is accepted and commissioned, a new cycle of planning and implementing the next change can be performed in queue. The cycle never ends according to the process of continuous improvement.

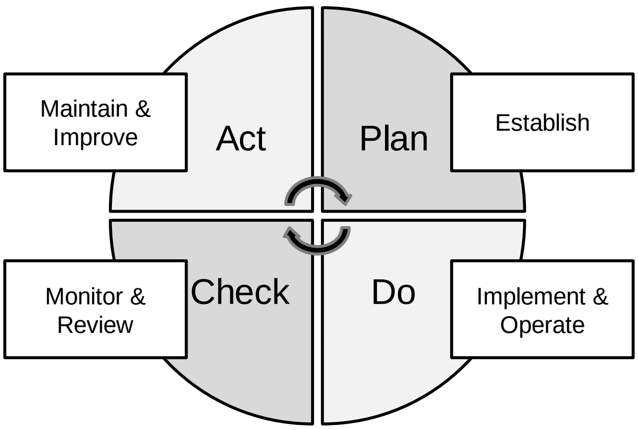


Figure 6-1 PDCA cycle [MN06]

According to [Dö07], thinking in intermediate goals can be advantageous especially when the final target and means of being successful in that specific problem are unclear. Within the context of Industry 4.0, uncertainty is due to the very fast technology innovation cycle. Manufacturing systems are not able to adapt so quickly to technology changes, therefore the target of the migration cannot be very clear from the beginning but could change according to external conditions.

When considering uncertain goals, the continuous improvement represents the only applicable approach to migrate towards cyber-physical production systems and beyond.

6.1.2 Options Investigation

Numerous technologies have been developed within the past years for flexible and reconfigurable production systems. However, their real benefit is still unclear due to the lack of implementation of CPS concepts and IoT technologies in real industrial environments. Therefore uncertainty does not only refer to what will happen in the future scenario of production systems but also to the set of possible technologies and methodologies to achieve that scenario [Ch09].

Solution options to achieve a predefined goal to migrate towards Industry 4.0 can be various. As these options are uncertain, they need to be systematically and carefully investigated [Lo08].

The success of an innovation process is determined by the “fuzzy front end” [Ke02], i.e. the early phase of the innovation process (Figure 6-2), which provides the basis for the innovation projects [DS12]. The term “fuzzy” is related to the market and technology uncertainties of the pre-development activities of innovation projects. One of the main characteristics of the “fuzzy front end” of innovation is the importance to create and evaluate multiple solution alternatives to select the optimal one [DS12].

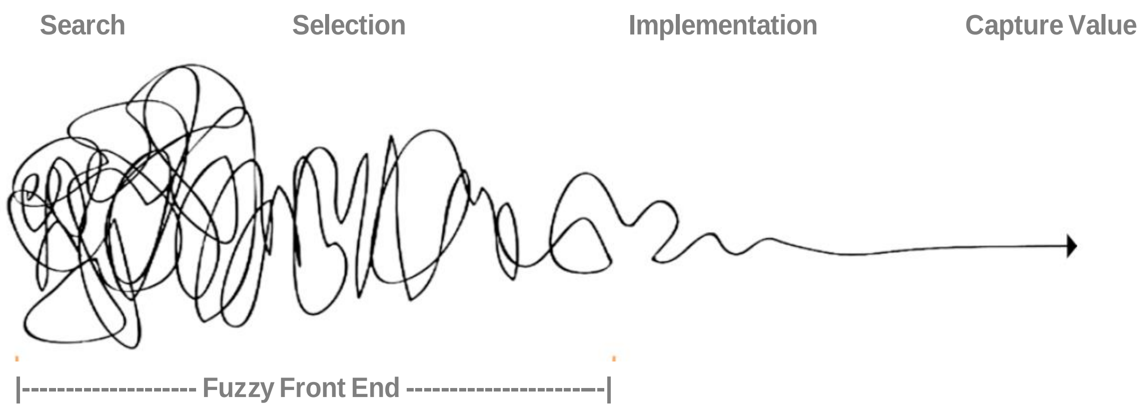


Figure 6-2 Fuzzy Front End [DT17]

Investigate options essentially means to generate a number of possible solutions and chose the optimal one from them. Options are selected according to the strategic decisions for migration of a manufacturing company, whose degrees of freedom are usually limited to its investments capabilities, legacy infrastructure and business identity.

According to [Lo08] the main goals of the investigation of options are:

- Enlarge the solution space so as to identify an optimal solution, which might not have been identified when considering only one solution idea;
- Strengthen the understanding of the problem and interdependencies within solutions through the development of solution options.

The options generated helps the overall understanding of a company's problem and support integrated decision making across the business, technical, operational and human aspects of a problem.

The investigation of options provides a way of thinking about opportunities, possible actions and decisions resulting in a wider range of possible measures than initially. This approach reduces the perceived initial uncertainty and provides viable alternatives to flexibly react to changing circumstance in the market environment or in the organization.

6.1.3 Multi-disciplinary Approach

The multidisciplinary, or interdisciplinary, approach allows for the combination of different subjects during a project. Developing smart systems, such as CPPS, requires the extensive collaboration of several engineering disciplines. As the same, knowledge on those multi disciplines and involved different subjects is required also in the definition of the specific migration strategy of a production system, taking into account the multitude of technical, operational, organizational and social dependencies. Like in every complex project, it is impossible to analyze the migration of a production system into a CPPS without touching different aspects. Therefore, the different domains need to cooperate closely in all stages of the migration.

Since many different disciplines and domains are involved (Figure 6-3), the main challenge is to handle complexity maintaining a holistic view of the production system during migration. Many interdependent dimensions and impact factors affect the decision of what Industry 4.0 technology offering to migrate a production system and how to do it. Thus, the migration decision becomes a multi-criteria optimization problem, in which interdependent specific aspects of the decision-making problem need to be addressed simultaneously.

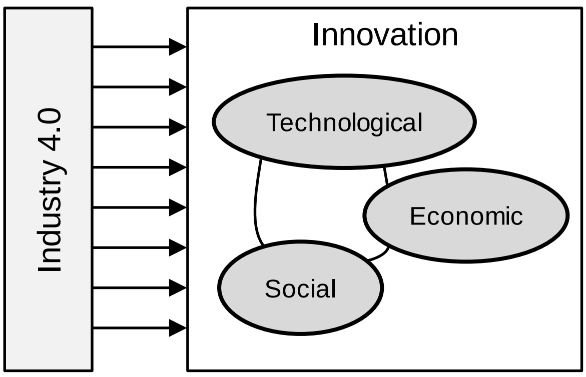


Figure 6-3 Innovation impact aspects related to Industry 4.0

The migration of production systems to CPPS environments entails concerns varying from technical and security problems to business, organizational and legal constraints

[Ju14]. As complex systems, CPPS are made of several components that interact with each other to accomplish functional and non-functional requirements. Organizations also have to take into account quality or economic requirements when adopting their applications to the new production environment. Issues to be considered are typically related to compatibility with legacy systems or restrictive internal policies that forbid organizations to move their proprietary software components [Ju14].

In the end, manufacturers have to evaluate many conflicting aspects before taking any decision on migration. All criteria are traded with one another together instead of in isolation. Indeed, improving a system in a dimension, e.g. increased modularity at shop-floor, can affect the system another one, e.g. investments. However, these aspect dimensions have different degree of importance for an organization and sometimes there are some constraints that an organization cannot overcome.

6.2 Migration Path Definition Logic

The migration process towards Cyber-Physical Production Systems follows a continuous improvement approach in order to maintain sustainability within the changing Industry 4.0 environment. By adopting Industry 4.0 solutions, industrial companies aim to remain competitive and, even more important, improve their own competitiveness on a long-term basis, taking into account that the long-term business sustainability depends on the ability to face increasing customer requirements.

Since the digital transformation and adoption of CPS has no clear industry-wide approach, only a stepwise approach can support manufacturers in adopting technologies with unclear benefit to smoothly migrate their production system in a heterogeneous environment.

Therefore, to cope with these uncertainties, the proposed migration approach supports the definition of the migration path towards Cyber-Physical Production Systems following an iterative and incremental approach, as defined in [CaL17a]. To this end, the logic of the migration process derives from the application of the Lean principles, according to the Toyota Improvement Kata [Ro10].

Figure 6-4 Definition of the migration path (1)

First, the process focuses on the definition of starting point and direction of the migration. In this step (Figure 6-4) the analysis of the long-term vision of the factory's business strategy is used as a guide to understand the direction in which the incremental improvements should be aimed towards. In the Industry 4.0 context, the long-term vision represents the target production system (e.g. the CPPS) that the manufacturer intends to achieve in the long run, following the company's strategy. Once the focus of improvement is identified, the current situation of the factory is analyzed to deeply understand the starting point of the migration.

To mitigate possible risks and obstacles due to the uncertainties coming from the market and technology areas, the migration path towards the long-term vision is decomposed in intermediate short-term goals that will be reached one at time (Figure 6-5). Therefore, the deep understanding of the current situation and the business long-term vision establishes the next target condition to be achieved in the short run. The achievement of the first short-term goal, as well as the following ones, represents a migration step in the direction of the long-term vision. Because even the target condition is outside of current knowledge, it is not possible to simply define a plan and execute it. Instead this step represents the "fuzzy front end" of innovation in which several possible solution options, in terms of new technologies, applications and systems, are considered and evaluated under different aspects, namely technical, operational and human dimensions of the factory.

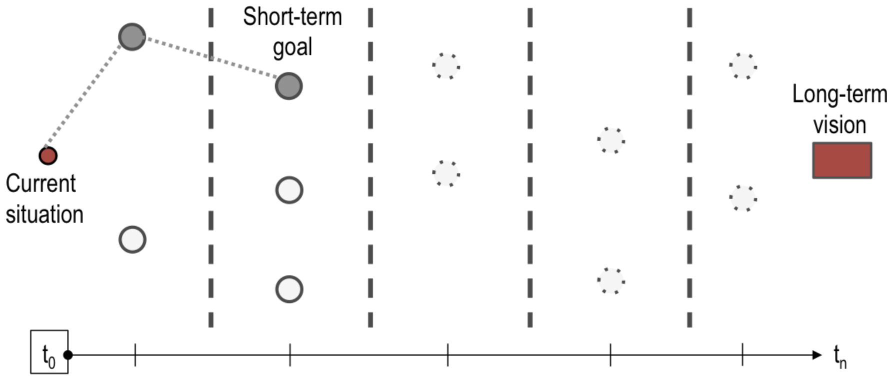


Figure 6-5 Definition of the migration path (2)

Following a typical PDCA cycle the selected solution options are planned and tested. This analysis can indicate situations where technical options are not supported by the technical, operational and human constraints of the current production environment. This can lead to the decision to reiterate the process in order to evaluate another candidate solution that passes the evaluation and decision step before being implemented (Figure

6-6). At this point the process converges into a specific solution to be designed, implemented and deployed to achieve the first short-term goal of the migration process.

Usually decisions taken under uncertainty depend on team knowledge and experience, but this step provides additional insights on the actual results and effect of uncertain decisions.

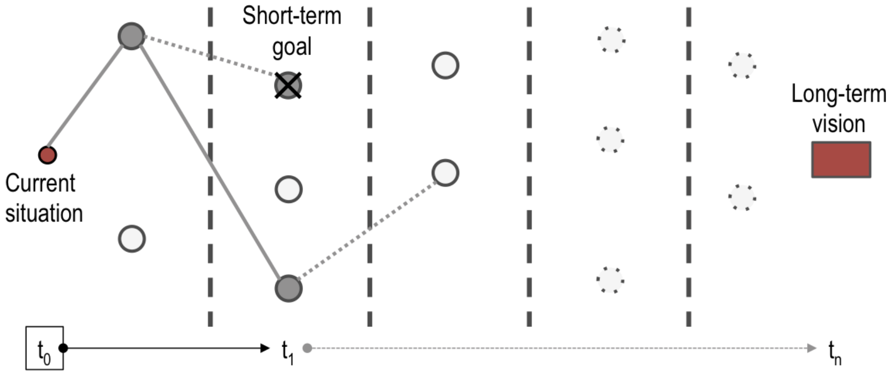


Figure 6-6 Definition of the migration path (3)

Once the first migration step is performed, i.e. the solution is fully implemented, the characteristics of the production systems, namely the new current situation, are changed (Figure 6-7). Now the production system is transformed and, like in the Improvement Kata, the process starts over again. As the same the market conditions, requirements and available technologies can be evolved. Consequently new possible solution options to achieve the next short-term goal and perform another migration step will be identified and evaluated based on the new current situation and target condition.

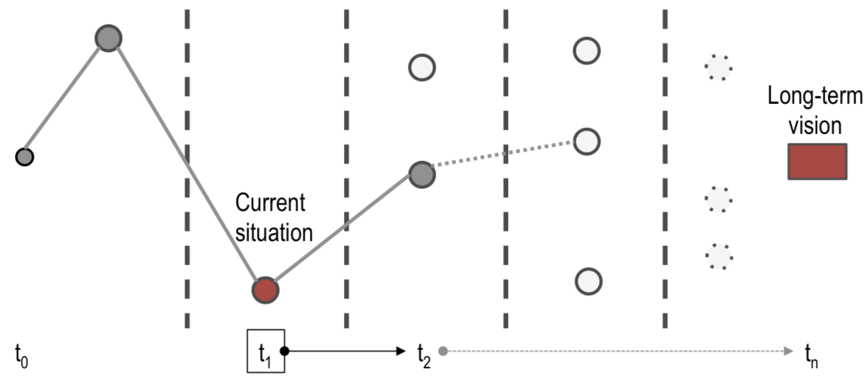


Figure 6-7 Definition of the migration path (4)

The objective of the migration process is to define the optimal path towards the long-term vision of the company by analyzing step by step a set of short-term goals. The principle behind is the continuous improvement of the production system by regularly defining the next short-term goal based on the new market conditions and adapting to continuously changing requirements. Following this approach (Figure 6-8), the production system can be smoothly transformed and improved at each migration step by implementing one-by-one new features.

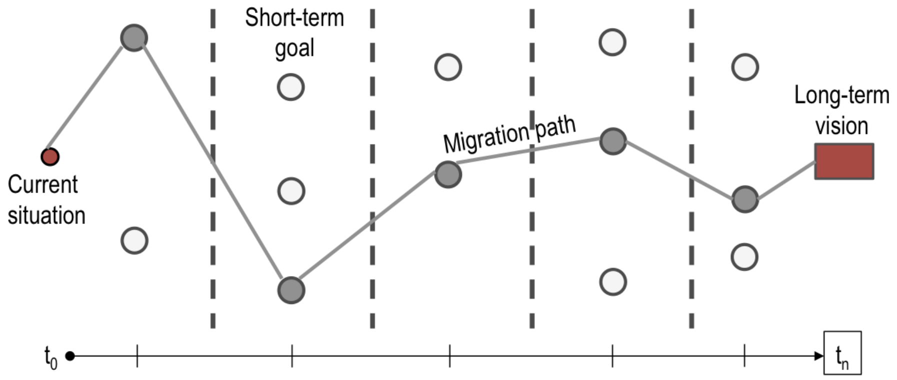


Figure 6-8 Definition of the migration path (5)

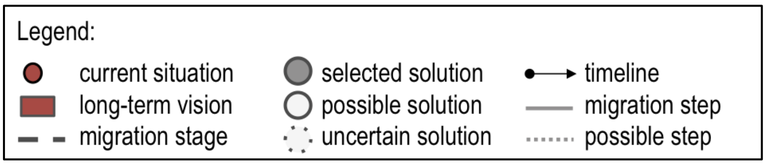


Figure 6-9 Legend of the migration path figures

6.3 5-phase Migration Process

Since the migration towards CPPS should follow a stepwise approach, each migration step will be performed once at time. Therefore, a 5-phase general migration process (Figure 6-10) that drives the identification, design and execution of the migration steps towards the long-term vision following an iterative and incremental approach supplements the described migration path definition logic.

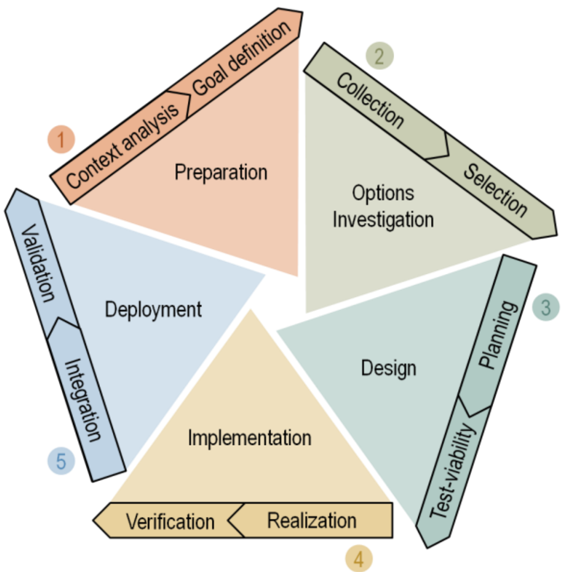


Figure 6-10 Migration process towards CPPS

The migration process has been proposed in [CaL17a] and takes inspiration from other industrial standard engineering processes that, even though developed for different purposes, can be applied to the migration towards CPPS in accordance with the characteristics defined in Chapter 2.4. The goal of the derived migration process is to support the continuous improvement of a production system targeting the Industry 4.0 paradigm. In order to carry out the migration path of a system, the process is repeated for each improvement step until the full achievement of the migration target.

The 5 phases of the migration process are: Preparation, Options investigation, Design, Implementation, and Deployment. The following sections describe in details the process' phases, while the methods and tools embedded to each phase are presented in Chapter 6.4.

6.3.1 Preparation Phase

The holistic migration process towards CPPS starts with the Preparation phase.

Like in every engineering design process, the first step consists in the definition of the problem or need. The problem statement is usually defined in the form of "[Who] need(s) [What] because [Why]" which leads to the definition of system's requirements in order to understand the stakeholders' needs and the scope of the project.

Most of the analyzed migration processes in Chapter 3.2 start with a preliminary phase that focuses on the starting and final conditions of the migration. Particularly, technical and financial constraints related to the existing software environment are evaluated in order to identify information systems with high potential of improvement towards a defined target environment. This analysis is a bit more complex within the context of Industry 4.0 because it is important to understand how the implementation of cyber-physical production systems in an existing manufacturing environment could occur at the shop floor and also at a more strategic level.

The main goal of the Preparation phase is to analyze the current situation and the possibilities for improvements of an existing factory system. Considering requirements as decision variables on which it is possible to act in order to reach the defined goals, the KPIs related to the agile, business and functional requirements are defined. In this way it is possible to maximize the real impact of the implementation of cyber-physical production systems and simplify their measurement.

According to the migration path definition logic, the outcomes of this phase are the current situation and the long-term vision of the migration for the considered production system, which are derived from the activities of *context analysis* and *goal definition*. The long-term vision, namely the business long-term goal, defines the direction of the migration in the long run according to the company's business vision. In parallel, the current situation and context of the factory production systems are assessed with the purpose of fully comprehend all the existing interactions within the system and recognize those system components that need to be upgraded or replaced.

The analysis of the current situation and the long-term vision represent the first tasks also in the XIRUP and MASHUP processes. The goal is to compare the business and functional requirements to the legacy systems in order to identify if and what new alternative systems are necessary to fulfill those requirements. To this end, assessment criteria are used to measure and verify the compatibility of legacy systems and new technologies with the advanced industrial requirements [Me17].

Based in all the information gathered and established during this phase, the target condition is defined and then, coherently with the established target condition, a preliminary risk and impact analysis is performed. This allows the company to decide whether is possible to proceed with the migration process or there is the need to reconsider some conditions, and depending on this decision the migration process can continue or the preparation phase has to start over.

The preliminary analysis of the migration feasibility must be conducted from different perspectives. The Butterfly methodology, the Cloudstep process and the XIRUP aim at justifying the migration investigating risks and benefits from technical and economical perspectives already at the beginning of the process, while the SMART process evaluates migration costs and efforts only after the development of the target solution.

In HoMoCPPS, the Preparation phase involves different organization roles in order to collect requirements and information about current issues from more different points of view, generating a more comprehensive overview of the system's needs and possible constraints for the migration. The goal is to derive few possible scenarios for the target system in order to support the analysis and generation of a set of concrete migration options.

6.3.2 Options Investigation phase

The Options Investigation phase deals with the collection and evaluation of different possible migration solutions aiming at identifying the optimal migration steps towards the long-term vision defined within the previous phase. This phase is particularly significant with respect to the discussed requirement of including options in Chapter 2.4 since it leads to the collection and selection of the optimal solution option among numerous available ones.

First activity concerns the identification and *collection* of the available technologies that can be implemented in the considered factory's scenario to achieve the first short-term goal. The collection of information is generally a time-consuming task. Possible technologies include solutions internally developed or provided by third-parts, namely the company's technology providers. Moreover, the collected solutions focus on the current issues, which have been identified in the Preparation phase, to be solved to enhance the production system in order to provide quick benefits but still in the direction of the Industry 4.0 vision.

Processes like the SMART and SOAMIG considered different alternatives and possibilities but did not provide a way to evaluate them in order to identify and select the optimal one.

In HoMoCPPS, based on the information derived from the previous phase, the collected options are then assessed in order to analyze the suitability of the existing technologies to reach the established goal or explore the possibility of developing new technology solutions. The evaluation of migration options is based on the business strategy and key performance indicators of the company. These elements are important to guarantee the benefit of the implemented solution, providing value-added to the system at each small migration step.

To evaluate each technology solution towards cyber-physical production system, Meyer et al. [Me17] derived a set of eleven criteria from the Partovi's strategic evaluation methodology for manufacturing technologies. These assessment criteria are listed below:

1. *Usability: degree of usability in manufacturing*
2. *Maturity: development status and readiness degree*
3. *Automation: level of automation*
4. *Integrity: level of integrity within other systems*
5. *Benefit: economic profit*
6. *Substitution: ability to be substituted by another competing technology*
7. *Availability: availability and support on the market*
8. *Potential: potential for the future market*
9. *Robustness: robustness and susceptibly degree*
10. *Security: availability of security mechanisms*
11. *Industry 4.0: relevance to Industry 4.0*

The *selection* of technologies and systems for the target condition is the activity that follows the assessment of the collected information. Particularly relevant for the evaluation of the solution options is the recognition of the critical dependencies of the solution within the production ecosystem. In fact, the new solution will impact legacy systems, current production operations and human resources. The misidentification of the critical interdependencies at technical, operational and human dimensions of the factory can lead to the failure of the migration process towards cyber-physical production systems.

6.3.3 Design phase

The Design phase addresses the detailed definition of the selected solution option and its integration with the legacy systems involved in the migration scenario.

The design phase is common to all migration strategies and at the end of this phase a migration plan must be defined in order to proceed with its implementation. This phase is initiated with a detailed description of the target system, namely defining the inherent functionalities, set of components, information flows and connection with legacy systems. This is followed by the *design* of the target system and the definition of the components, such as new tools and adaptors to connect the legacy and target systems.

In Butterfly, MASHUP and IMC-AESOP the design phase consists in the definition of the target solution based on the predefined needs and requirements. Since those processes do not consider a stepwise implementation of the solution that will replace the old one, they do not address the possible integration with legacy systems. Differently, the SOAMIG process describes in this phase also the interaction of the developed solution within the environment and its technical feasibility towards an iterative migration of the legacy systems.

Different technical disciplines can be involved in this phase depending on the complexity of the solution. Since one of the main goals of the Industry 4.0 paradigm is to integrate heterogeneous systems, designs will focus first on the new architectural composition of legacy and new applications and hardware and on their automation control structure. Emphasis will be put on the interfaces between different systems within the new decentralized control architecture, required information flows, interactions with human resources, and new process operations.

Designs can be managed differently according to the variety of disciplines involved and corresponding perspectives. But then the configuration of the solution must specify the connections between legacy and new components, such as the connection of communication devices to a network, data flows and their relations, and input/output signals [Wa10].

The HoMoCPPS aims first at designing the target system and subsystems at high level highlighting their impact on the legacy environment's structure and the required new interfaces to integrate them. Of course, the system's components need to be designed more in details in a second stage to be tested before the implementation phase.

Once the target system and its components are defined, *viability tests* are performed to ensure that the system is compliant with all required activities. Test-viability is fundamental to ensure the heterogeneous systems integration and the viability of the solution. Depending on the test results it could be necessary to re-evaluate the target system and start a new iteration of the design phase to identify a better solution before proceeding with the definition of the implementation and deployment migration plan.

Test-viability includes a risk analysis to assure that the risks associated to the migration towards the new system solution are acceptable, according to the obstacles and constraints defined within the preparation phase. Moreover, a contingencies' plan can be elaborated based on the outcomes of the risk analysis.

Finally, a strategy to execute the migration is selected. This selection concerns all the information gathered in the previous tasks, as well as the criteria defined in the Preparation phase. According to Chapter 3.2, the implementation of the new system solution could be performed following a Big-Bang strategy, i.e. the new system replaces the old system in a single moment time, or a Parallel Systems strategy, in which old and new systems run for a certain period of time until the new system reach the desired level of trustiness, or again a Phased Implementation strategy, especially in case of very complex designed solutions.

The selection of the implementation strategy mainly depends on the complexity of the solution from a technical viewpoint. However, most changes in an organization have a social component [vK19]. The social challenges that usually accompany the implementation of a change are related to education and training of involved human resource, which can be done before a Big-Bang implementation or during a Parallel System strategy.

6.3.4 Implementation phase

The purpose of the implementation phase is the realization of the solution system components [ISO/IEC/IEEE 15288]. System components can be hardware, software, operational resources or services. In other words, everything that will be needed to deploy the new solution and, thus, migrate the production systems, is arranged. Therefore, it is important to clarify what must be done, by whom and when.

The implementation phase is the doing phase, in which the solution is realized and verified, according to the list of requirements and specifications created in the preparation and design phases, respectively. Thus, the individual solution components are configured for a specific task, according with the requirements [Wa10].

Usually the system is tested internally as part of the verification process, like in XIRUP and SOAMIG. More in general, implementation indicates the execution of a plan for a change, therefore the term includes also developing, testing, and other activities that support the change [PNN09]. Specifically, in HoMoCPPS the focus is on the system *realization* activities that are usually taken after a positive testing phase, which shows that the change leads to improvement, but before scaling up this change to new areas of the organization. The goal is to ensure that the infrastructure is in place to make the change successful and durable. To this end, this phase must include training, documentation, standardization, adequate resourcing, and social considerations.

The defined implementation plan and solution are verified once again before being deployed in the real production environment. The *verification* is performed to check the correct implementation of the target solution, e.g. the architectural characteristics or the design properties of a solution component. Each solution component is thus compared against its specified requirements. The verification applies to both software and hardware systems, but the related processes and approaches can be various.

6.3.5 Deployment phase

The deployment phase is common to every migration process and consists in the actual transition of the production system into the new-implemented solution. The installation of the verified system comprehends the activities of integration and validation of the solution in the real production environment.

The *integration* is performed according to the implementation strategy defined in the previous phase. Special attention is paid to the integration of new solution system with the legacy systems of the factory. Within HoMoCPPS, the integration considers the deployment of the system components not only with reference to their technical feasibility, but establishes also their integration with operations and humans, both legacy and new. Production, maintenance and designing processes will be adapted to the new-implemented configuration of systems. As the same, the human roles and tasks must be aligned with the new technical and operational solutions.

The solution components will be integrated according to the implementation strategy considered in the previous phase, i.e. Big Bang, Parallel Systems, and Phased Introduction.

The *validation* process finally checks that the solution system provides the function intended and that all boundaries among legacy and new system elements have been correctly identified and described. Usually a complex solution system includes physical, logical, and human systems interfaces and interactions. The validation checks the performance of the overall system and its elements and also the fulfillment of design requirements. The overall goal is to ensure the correct functionality of the new production system, as intended, according to its business goals and stakeholders requirements. Approach and methods to perform the validation are usually very similar to the verification processes and, as the same, depend on the type and complexity of the considered systems.

Once the system is validated, the migration step is completely executed and the production system is transformed. At this point the HoMoCPPS process starts again with the Preparation phase, since the analyzed system has a new “current” situation. Following the same process the next migration steps will be defined until the long-term vision is fully achieved.

6.4 Methods and Tools for Process Execution

To overcome uncertainty and mitigate risks related to the migration of manufacturing industries towards CPPS, new methods and tools are required to guide the industrial transformation and support the alignment of business strategies and manufacturing operations [SES16]. The process can be executed using different existing engineering methods and tools. This section presents three solutions developed appositely for the Preparation, Options Investigation and Design phases.

6.4.1 Questionnaires

Experience from discussion and workshops within the projects have shown that it is difficult for companies to understand Industry 4.0 and CPPS concepts. First, they are not able to link the idea of Industry 4.0 with their current business strategy in their specific domain. In addition, they are not able to understand what is their current state related to the digital revolution.

An important tool to support the identification of the optimal migration strategy within a company is the questionnaire. In HoMoCPPS the “Assessment Questionnaire” has been developed, as described in [CaL18] and [FA17], to support the analysis of a company and drive the discussion with manufacturers in order to identify main issues, obstacles and opportunities related to the implementation of CPPS in their production systems.

The Assessment Questionnaire aims at collecting information about the current state of the factory at technical, operational and human dimensions. The overall goal is to provide a good basis to holistically evaluate the alternatives under different aspects. In fact, when evaluating the actual capabilities of a company, not only the available technologies and installed devices should be considered but also their processes and organization structure, which exploit the full potential of these technologies.

The questionnaire, presented in Annex – Assessment Questionnaire [FA17], is made of around 60 questions structured in 7 sections concerning technical, operational and human dimensions of the factory (see Table 6-1). The focus of the questionnaire developed is on the manufacturing plant.

Scenarios	Dimension	Topics
Automation	Technical	Current automation system in production, i.e. the structure of the automation architecture and the legacy software and hardware; the type of connectivity among these systems; and the existing security and access control mechanisms.
	Operational	Capability to manage and integrate automated tasks into a cohesive process or workflow for IT and the business (e.g. order processing, equipments reconfiguration, quality inspection, and material planning).
Analytics	Technical	Availability of data and information needed to carry out the analysis to provide the value added to management approach, e.g. collecting and processing data devices, quality and performance monitoring systems.
	Operational	Capability to manage a basic manufacturing process controlling the input factors and to monitor the uncontrollable variables aiming at evaluating and optimizing the output responses (e.g. performance and maintenance analytics).
Virtualization	Technical	Availability of specific visualization and simulation tools, 3D layouts and generation of digital models.
	Operational	Capability to test equipment and production processes based on simulation activities; production optimization based on What-If scenarios and accurate models.
Human		Current roles and skills; health and safety measures; privacy; human-in-the-loop; human-in-the-mesh; trainings programs.

Table 6-1 Topics of the Assessment Questionnaire

Each question has a predefined closed set of answers that are ranked according to a normative description based on the CMMI, which span from Level 1 to Level 5, i.e. from the lowest to the highest respectively. These levels are based on the principles of both the CMMI (Capability Maturity Model Integration) framework [CM02] and DREAMY model (Digital REadiness Assessment MaturitY) [DCa17], which are reported below:

- *Level 1* – The production system has not the proper technologies and IT tools for implementing a digital infrastructure; there is no engineering activity to ensure repeatability or extensibility; and only dividing workforces.
- *Level 2* – The production system lacks of enabling technologies to follow and control the decision taken by supervisor; processes are partially planned based on the planner experience; and humans present lack of related knowledge and skills.
- *Level 3* – The constraints on the production system technologies avoid a full interoperability and interconnection; good practices are implemented but with integration and interoperability gaps; and skills to guide job activities are not well defined but there is a little synergy in the organization.
- *Level 4* – The control architecture is more sophisticated and is able to optimize the change process to have a full collaboration; the processes are fully planned and implemented using common and shared standards; the organization uses quantitative analysis of workforce capabilities to predict organization performance.
- *Level 5* – The production system is based on a solid technology infrastructure that enable systems full interoperability and interconnection; the process is digital oriented and based on fast, robust and secure information exchange; the organization is focused on continuous improvement and change management is dealt according to well-defined principles.

The assessment procedure is implemented in three phases:

1. In the first phase, manufacturers or other collaborators and employees responsible for the migration towards CPPS are invited to an interview in which the Assessment Questionnaire is used only as guideline to conduct a structured discussion and gather all the relevant information;
2. Second, the interview’s results are assessed in the Assessment Questionnaire, in which a score is assigned to each topic of the three dimensions according to the pre-defined maturity levels scale;

3. Finally, an overall report is generated, which includes all the relevant information about the AS-IS situation of the evaluated factory and the main issues, obstacles and opportunities related to the implementation of CPPS solutions.

The output of the interview is a set of scores, assigned to the factory, which are related to its digital maturity at technical, operational and human dimensions. These results can be aggregated in a spreadsheet, like Microsoft Office Excel, that helps the identification and visualization of the factory's digital maturity for specific topics. Indeed, using this kind of tools, the strengths and weaknesses of the assessed factory can be easily identified. In particular, the overall score can be calculated and represented in charts, such as radar charts.

This maturity assessment is a powerful tool to be adopted for the Preparation phase of the HoMoCPPS process. The criticality analysis of the factory enables the identification of the weakest points that subsequently drive the improvement of the production system at technical, operational and human dimensions. This analysis concerns at identifying the application fields to focus on, considering the business goal and the barriers and constraints in place.

The maturity scores of the Assessment Questionnaire are thus adopted to assess in a measurable way the state of practices in a company and stimulate thinking on the needs of factory's improvements that can be enabled by Industry 4.0 technologies. In fact, after this phase the manufacturers can have an idea on what should be improved first and thus identify the short-term goals to be achieved within a migration step.

6.4.2 Migration Matrix

The "Migration Matrix" is a visual tool developed and described in [CaL18] and [FA18] to analyze factory's assessment of their current situation in terms of digital maturity based on their existing technical systems, operations and humans. Many on-line tools already exist, enabling companies to self-assess their readiness for the digital transformation, but the Migration Matrix aims at providing also a structured guideline to identify the fields of action in order to face the migration towards CPPS according to their current situation.

The Migration Matrix is based on the "Toolbox Industrie 4.0" of the VDMA Guidelines in [SAF16] aiming at providing a visual tool to holistically understand the current condition of the factory and evaluate possible alternative migration scenarios towards a short-term goal. Indeed, it determines which capabilities a manufacturing organization needs to acquire in order to successfully implement CPPS technologies. Furthermore, it serves as migration roadmap towards Industry 4.0 supporting the identification of priorities and interdependencies among different solutions at technical, operational and human dimensions of the factory to evaluate what should be migrated first.

The overall goal is to provide manufacturers with a description of different migration scenarios. The Migration Matrix shows how the migration solutions can improve the production systems and what are the other entities and processes actively or passively involved. Based on a complete and comprehensive observation of the company weakness and strengths, practices for applying the transformation to CPPS in a consistent way can be derived.

This visual tool is structured as a table in which rows and columns reflect the elements defined in the Assessment Questionnaire:

- The rows represent the relevant application fields with high potential of improvement by CPPS concepts implementation on the considered production system. They refer to the derived technology innovations, factory process maturity and human roles. Therefore the rows contain the same set of application fields classified in technical, operational and human dimensions.
- The columns describe the development steps for each application field towards a higher level of production flexibility, intelligent manufacturing and business process towards the realization of a CPPS for each specific application field. They represent the same 5 incremental levels of digital maturity, from Level 1 to Level 5.

As shown in Figure 6-11, the three rows represent the three macro-dimensions of the factory, while the five columns depict five levels of production system’s digital maturity.

The rows of the matrix provide a holistic view of the aspect dimension of the factory (see Chapter 2.3). This set of dimension can be extended to other areas according to the scope of the migration and the manufacturing organization. As a generally applicable matrix, the main application fields of a factory have been classified here as technical, operational and human dimensions, according to the Assessment Questionnaire. These dimensions may not be complete but they are sufficient to rank the actual situation of the factory and identify possible action of general improvement.

The columns of the matrix represent the scale of levels used to define the digital maturity of a manufacturing company through the Assessment Questionnaire. The specific maturity levels scale for the technical, operational and human dimensions are represented in details in Table 6-2, Table 6-3 and Table 6-4.

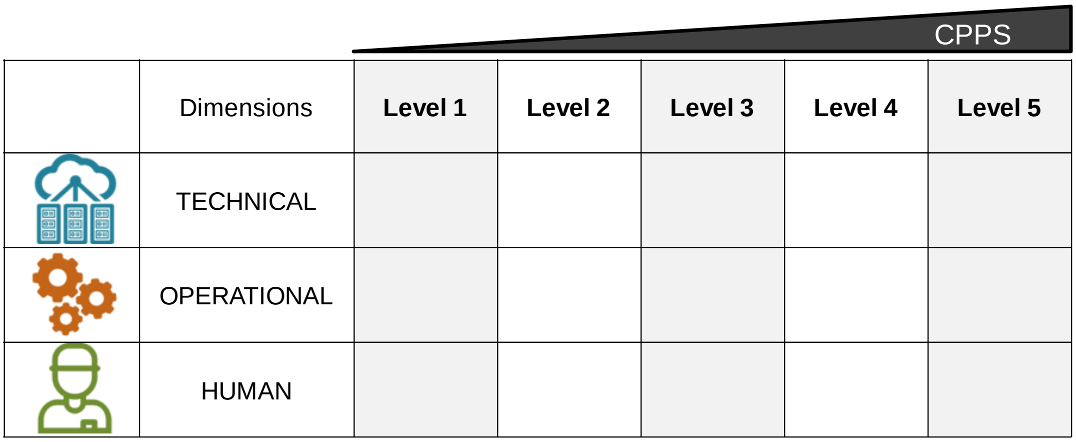


Figure 6-11 General Migration Matrix (empty)

Maturity scale for the Technical dimension	
Level 1	No proper technological and IT tools for implementing a digital infrastructure
Level 2	Lack of enabling technologies to follow and control the decisions taken by supervisors
Level 3	Constraints on the enabling technologies that avoid a full interoperability and interconnections
Level 4	IT and other key technologies allow to have dynamic and sophisticated architecture to optimize the change process and empower new models to have a full collaboration
Level 5	Enabling digital technologies that ensure a full interoperability and interconnection that lead to decentralize the typical automation architecture

Table 6-2 Maturity levels scale for the Technical dimension

Maturity scale for the Operational dimension	
Level 1	Poorly controlled processes with only reactive process management and no engineering activity to ensure repeatability / extensibility
Level 2	Partially planned processes and choices driven by the experience of the planner
Level 3	Implementation of good practices but with lack of integration and interoperability
Level 4	Fully planned and implemented processes, with common and shared standardization and best practices related to organization and technologies
Level 5	Digital oriented process with high potential growth organization and fast, robust and secure information exchange

Table 6-3 Maturity levels scale for the Operational dimension

Maturity scale for the Human dimension	
Level 1	Lack of coordination in performance with displacement of responsibilities dividing workforces
Level 2	Lack of related knowledge and skills, weak communication and low morale, with unclear performance objectives or feedback
Level 3	Low synergy in the organization, lack of standard of performances, with knowledge and skills to guide job activities are not well defined
Level 4	Ability to predict organization performances, using quantitative analysis of workforce capabilities
Level 5	Focus on continuous improvement. The established results of the quantitative management activities are taken as starting point of improvement. Change management is dealt according to past procedures and based on principles

Table 6-4 Maturity levels scale for the Human dimension

The matrix is used within the migration process to represent the AS-IS and TO-BE situations of the factory and, therefore, to support the identification of the areas in which a manufacturer needs to act matching the needs of the organization and the estimation of the overall benefit. Based on the measure of the current digital maturity of the factory, alternative concrete solutions can be mapped into the same matrix towards the achievement of a higher maturity stage in order to maximize the economic benefits of Industry 4.0 and minimize the correlated risks.

For example, as described in Chapter 2.1 a traditional factory will benefit from the adoption of Plug-and-Produce technologies at equipment level with the improvement of the shop-floor reconfiguration capabilities. From a technical point of view a plug-and-produce production system requires a decentralized automation control architecture that enhances the automatic identification and integration of new components, as well as their reconfiguration during the production process without additional adjustments of the overall control. In order to do so, system components will need to be connected to communicate and initiate parameters exchange at the beginning of the production, this requires standard communication protocols.

Besides new technical characteristics also operational and human aspects need to be considered. In fact, plug-and-produce capability could be seen as a crucial solution to reduce time and cost involved not only in manufacturing process but also in process design and process development. Therefore the information between engineering and manufacturing has to be harmonized by means of an overall data backbone for all processes and products that will integrate the information flow between manufacturing and engineering domain. In addition, the MES can automatically provide execution data to ensure holistic and reliable product information that, being documented and available in both systems, can be considered as a strategic asset to improve the maintenance, repair and optimization process.

Also, the role of employees can be affected by the new technological and operational landscape: on the one hand, some manual tasks or scheduling decisions are taking over by the systems; on the other hand, some new tasks are added to supervise the systems, monitor the KPIs, and address the problems. It is important for operators to stay in the loop of control of the process and be aware of what are the states and activities of the technological systems.

The reference sample in Table 6-5 shows how to map a migration scenario using the Migration Matrix tool, in which the red boxes represent a partial AS-IS situation of the company, as derived from the questionnaire’s answers, while the green boxes indicate the TO-BE situation according to the highest maturity level of the Migration Matrix. More details about this use case example can be found in [CaB18].

It is important to clarify that the Level 5 does not always represent also the goal of a specific migration scenario. Specific business requirements and needs could lead to a

Level 3 or 4 of digital maturity because of financial constraints or simply advantages that a lower level can bring to a certain migration scenario.

	Level 1	Level 2	Level 3	Level 4	Level 5
	Equipment / machinery connectivity and communication protocols				
	Not available	Basic connectivity	Local network (LAN/WAN)	Networked with vendor specific API	Networked with I4.0 standard communication protocols
	Production data monitoring and processing				
	Not available	Locally available (per equipment)	Centrally available through SCADA	Available and analyzed through MES	Available ad analyzed through the Cloud
	3D layouts, visualization and simulation tools				
	CAD systems not related to production data	CAD systems manually feed with production data	CAD systems interfaced with other design systems	CAD systems interfaced with intelligent systems for fast development	Fully integrated CAD systems with intelligent tools for interactive design process
	Reconfiguration of production equipment and processes				
	Manual	Locally managed at machine level (PLC)	Centrally managed from SCADA	Centrally managed by MES	Centrally managed according to ERP
	Product optimization				
	Not available	Rare offline optimization	Offline optimization based on manual data extraction	Manual optimization based on simulation data	Automatic optimization based on simulation services
	Availability of production process models				
	Not available	Models defined in Excel with limited usage	Models defined with limited specific functions	Models integrated with business functions	Models integrated with several different functions
	IT Developer				
	Not available	External service provider	Internal for traditional IT systems	Internal for specific digital systems	Internal for all systems from Field to Cloud
	Impact on Operator, Product Designer, and Production Engineer				
	Still unclear	Indentified in general terms	Analyzed	Defined	Implemented in continuous improvement

Table 6-5 Example of Migration Matrix

A migration scenario described within the matrix always represents application fields from all the three dimensions of the factory (technical, operational and human) for that specific use case.

As in the example, each migration scenario is represented using the Migration Matrix format and refers to a specific short-term goal. This means that a Migration Matrix does not represent the whole factory but only the relevant application fields related to a specific use case. In order to define a migration step, different short-term goals are evaluated within the matrix deriving a set of possible migration scenarios. These migration alternatives are then evaluated according to the business strategy, considering also strengths and weaknesses points.

In conclusion, the Migration Matrix tool results in the formulation of a stepwise roadmap towards CPPS in all relevant areas of the factory.

By means of the derived Migration Matrixes, based on the identified obstacles and opportunities, manufacturers can have a clear view of their AS-IS situation and prioritize the possible next migration steps based on the perceived benefits at business level and feasibility of the solution in terms of implementation. Once the current condition of the factory is mapped into the matrix, manufacturers and people involved in the definition of the migration strategy should explore the opportunities of improvement related to the implementation of digital technologies at factory level, including operations and humans.

The overall goal of the Migration Matrix tool is to provide a succession of digitalization stages that bring to the industry some initial benefit of the Industry 4.0 paradigm while minimizing initial investments and related implementation risks. In fact, the assessment of current processes and the subsequent identification of areas requiring action provide companies with specific and practical guidance for shaping their digital transformation.

6.4.3 Model-Based Design

Chapter 4.3 highlighted the potential of model-based approaches in supporting the design of complex systems through a holistic view of the problem: from the business requirements definition to the design and simulation of the solution system. In the context of definition of migration steps towards a stepwise implementation of CPPS, model-based design techniques can be used to describe the correlation between the new solution system and the legacy applications, devices and humans of the current production system.

The presented migration approach uses MBSE to model the target solution, design the required integration measures of new systems and identify their impact on the legacy production system. For example, it helps in the identification of new required physical interfaces to enable the systems communication, or new humans' skills related to the use of the new system solution. By using a semi-graphical modeling language, typical for MBSE, the impact of the new solution on the existing production systems can be easily captured. The MBSE approach for migration is also presented in [CaL17b].

If the Migration Matrix supports the identification of possible migration scenarios to achieve a specific short-term goal, the MBSE aids with the modeling of the technical solution and the identification of criticalities that need to be considered within the migration step. In fact, the system modeling language SysML enables a holistic evaluation of possible migration scenarios under different aspects. From a technical viewpoint, the model of the current system (AS-IS) and target solution (TO-BE) for a specific migration scenario identifies the new technologies required and additional components necessary to integrate the new solution with the legacy systems. From the operational and human viewpoints, the SysML can be used to describe the AS-IS and TO-BE workflows analyzing new or changed human and systems operations required by the considered migration scenario. To this end, SysML diagrams are used within the Design phase of the migration process to depict the internal structure of the solution system and the behavior of the respective entities involved in a migration scenario.

The Functional Analysis of the MBSE enables the development of systems functional requirements to obtain the functional definition of the solution system. The Use Cases are derived from the migration scenarios identified with the Migration Matrixes and constitute the basis to develop the system's structure and behavior.

The Use Case Diagram (UCD) is used to represent the macro-functional areas of the system considered within the defined migration scenario [HP01], highlighting which actors have a role in this scenario and how they interact with the system. Actors are not only humans but also external systems that are actively or passively involved [BCF18].

Taking into account the same example used to show the application of the Migration Matrix, besides the reconfiguration of production equipment, also other scenarios, such as the simulation-based optimization, can be modeled through SysML. In this way different migration solution options can be stored in the same SysML project. These scenarios are represented in a UCD as *use cases* of the systems, while the entities correlated to the scenarios are depicted as *actors*.

The use case described in Figure 6-12 refers to the actors involved in the reconfiguration of production equipment. In particular, by using the "generalization" notation, the general use case derives two specific use cases: the manual reconfiguration of equipment, which corresponds to the AS-IS situation; and the plug-and-produce-based reconfiguration, the TO-BE situation.

This type of diagram clarifies already at the beginning of the modeling activity which entities are involved in the migration process, typically not only machinery and equipment but also human operators and system applications. This UCD depicts the main actors involved in the specific migration scenario, which may be impacted by the new migration solution.

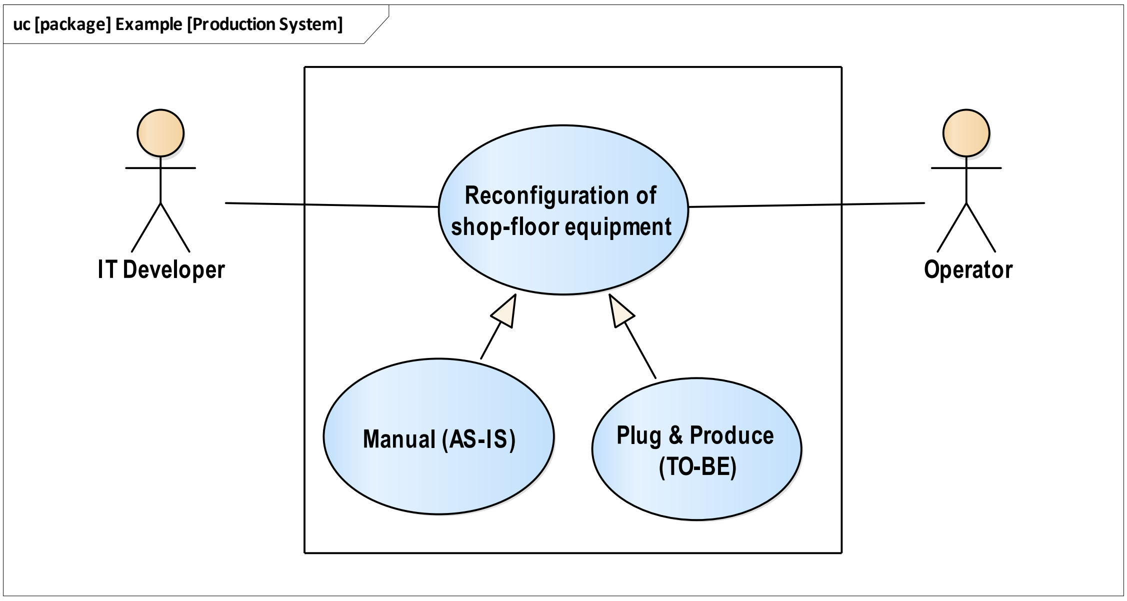


Figure 6-12 Example of Use Case Diagram

According to the MBSE approach described in [BCF18], functional and architectural analyses should follow the use cases definition in order to systematically and consistently design a complex system.

The functional analysis is performed for each use case and the other SysML diagrams used afterwards refer to the actors and their interactions indicated in the UCD. Once defined the context of the migration step, the system solution has to be detailed starting from its internal structure to the interaction among new and legacy system components and their behavior.

Structure and interactions between blocks are usually defined in MBSE by using SysML Internal Block Diagrams (IBDs) [Ro13]. IBDs can be used to represent the structure of a scenario in both the AS-IS and TO-BE situations of the migration in order to show the impact of change that the new solution will have on the current production infrastructure, which will be emphasized by means of semantic rules and a color code.

The IBD describes how the system components, represented as blocks, interact with each other by means of flow ports and connectors. In particular, the flow ports represent the physical or data interfaces and the connectors indicate the type of communication exchange between two blocks, i.e. system entities [CaL17b].

In order to classify blocks in old and new systems, three stereotypes have been defined:

- <<legacy>> – legacy entities (hardware, or software) of the existing production system involved in the considered migration scenario;
- <<new>> – new entities (hardware, or software) of the selected migration solution to be integrated within the existing production environment;
- <<human>> – human roles that deal with legacy and new entities.

The name assigned to the stereotypes can be different, according to the exigencies of the use case represented. For example, in Chapter 7.1.3 some blocks show the stereotype <<PERFoRM>> instead of <<new>> because they refer to a specific solution developed within the PERFoRM project.

In addition to stereotypes, blocks are distinguished by using the following color code:

- blue – legacy system components or human roles that remain unchanged in the new migration scenario;
- green – new system components or human roles of new migration scenario;
- yellow – legacy system components or human roles modified in order to be integrated within the new migration solution;
- grey – legacy system components or human roles not required anymore in the new migration solution.

Usually, within an IBD the actors at the left side provide an input to the system, while the actors at the right side receive the output. The functional elements of the system are described by parts, represented as *blocks*, while the arrows embedded in small squares at the parts' borders, i.e. the *flowports*, indicate the flow direction. The elements are connected through *links*, or connectors [BCF18].

The figures below depict the IBDs for the example migration scenario. In order to understand how the current production system is impacted by the new solution, both the AS-IS (Figure 6-13) and TO-BE (Figure 6-14) situations are represented.

The current situation consists in a manual placement of new equipment, which is configured by the IT developer and registered to a resource library in order to redefine the production schedule accordingly. One of the migration scenarios derived from the Migration Matrix is the implementation of plug-and-produce technology to easily reconfigure the shop-floor equipment using standard Industry 4.0 communication protocols and a Cloud repository that enables the fast synchronization of new equipment data with other applications, such as ERP system.

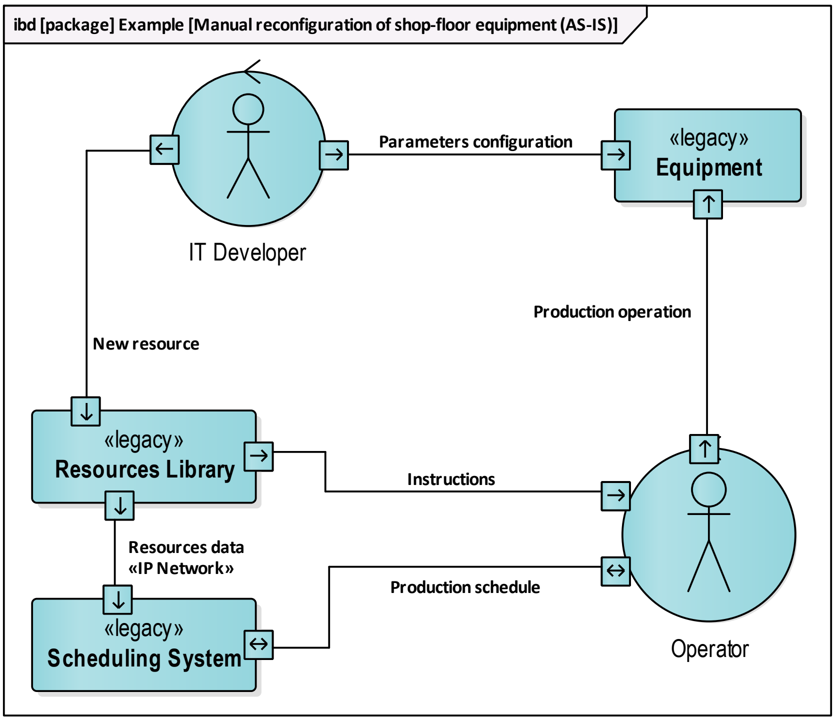


Figure 6-13 Example of Internal Block Diagram of the AS-IS situation

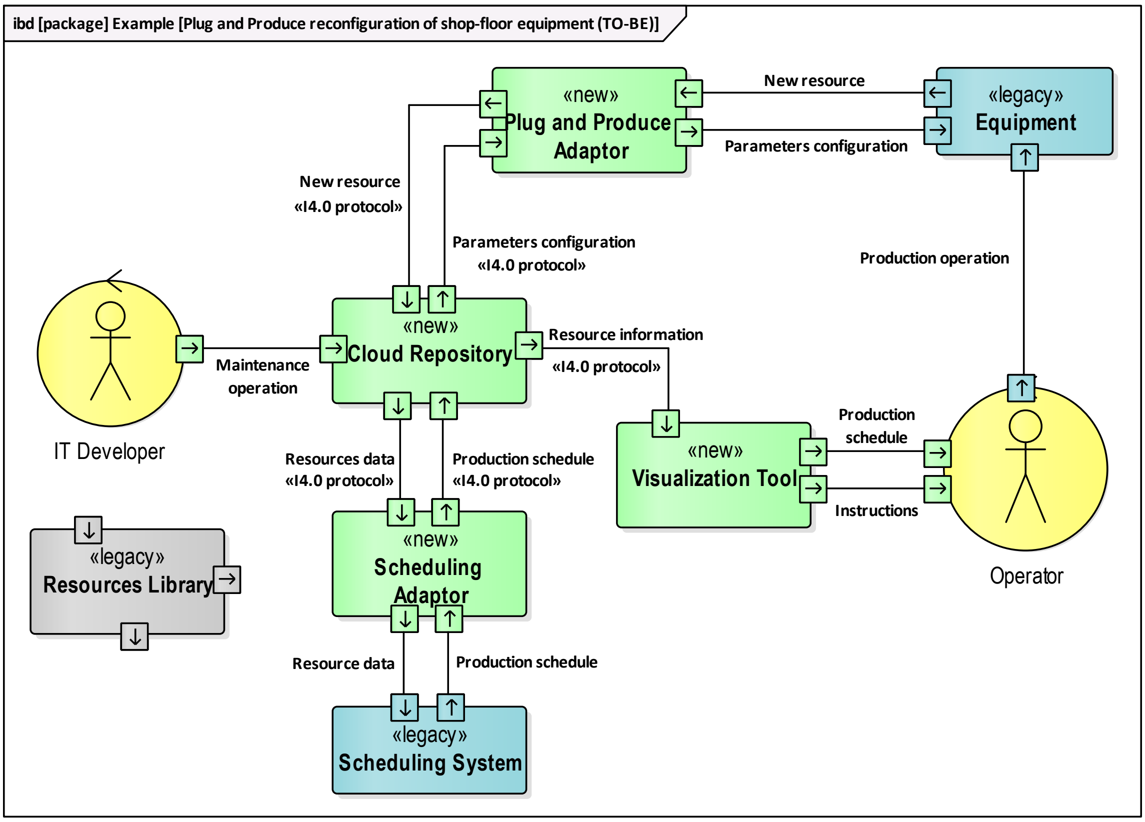


Figure 6-14 Example of Internal Block Diagram of the TO-BE situation

In this simple migration scenario, the goal is to implement plug-and-produce capabilities towards a faster reconfiguration of the shop-floor equipment as soon as a change is required, supported by a more distributed control architecture. In this case the legacy equipment needs to be provided with a plug-and-produce technology adaptor that enables the communication and synchronization of new equipment information through standard communication protocols. As the same, the scheduling system will be directly interfaced through another adaptor with the cloud repository, which is added to collect and make available all the information related to the integration of new equipment. A visualization tool will show the new instruction and production schedules to the operator. Since the automation control architecture is modified to enable the new communication flow, also the task and required skills of the IT developer need to be adapted.

The migration step involves not only the introduction of new equipment or applications but also a change in the workflow for each specific use case. To represent the functional behavior of the new system solution, the SysML “white-box” Activity Diagrams (ADs) are used [De14]. An AD is used in MBSE to model the behavior of a system in terms of activities and operations performed in sequence within a specific use case scenario. The considered sequence is not time-based but describes whether two activities are performed contemporarily (activities in parallel) or sub-sequentially (activities in series). In contrast to the concept of “black-box”, “white-box” in an AD means that each activity is specifically assigned to an actor of the system [Ro13]. This way of modeling is very useful when representing a change in a system operation because it emphasizes new human tasks or legacy systems capabilities required by the usability of the new system implemented.

Here the same color code of IBDs is used to emphasize the different type of activities:

- blue – activities already performed by legacy entities in the AS-IS situation;
- green – new activities performed by new entities of the TO-BE situation;
- yellow – new activities performed by legacy entities in the TO-BE situation;
- grey – former activities that are not required anymore in the TO-BE situation.

Typically “white-box” ADs are characterized by the presence of *swimlanes*, which split the diagram in rectangular frames to indicate which entity is responsible for each action [De14].

As described in Figure 6-15, the operator in the TO-BE situation is responsible for the plug-in of the new equipment, which automatically stores its data in the cloud repository through a plug-and-produce adaptor. Data collected in the cloud are available for the scheduling system, through a specific adaptor that translates data, and the visualization tool, which displays the operation instructions to the operator according to the new plugged-in equipment.

The IT developer will not be responsible for the configuration and synchronization of the new equipment anymore, since it will happen automatically through the plug-and-produce technology and the data available in the Cloud repository. However, he will take care of the new Cloud system and its maintenance.

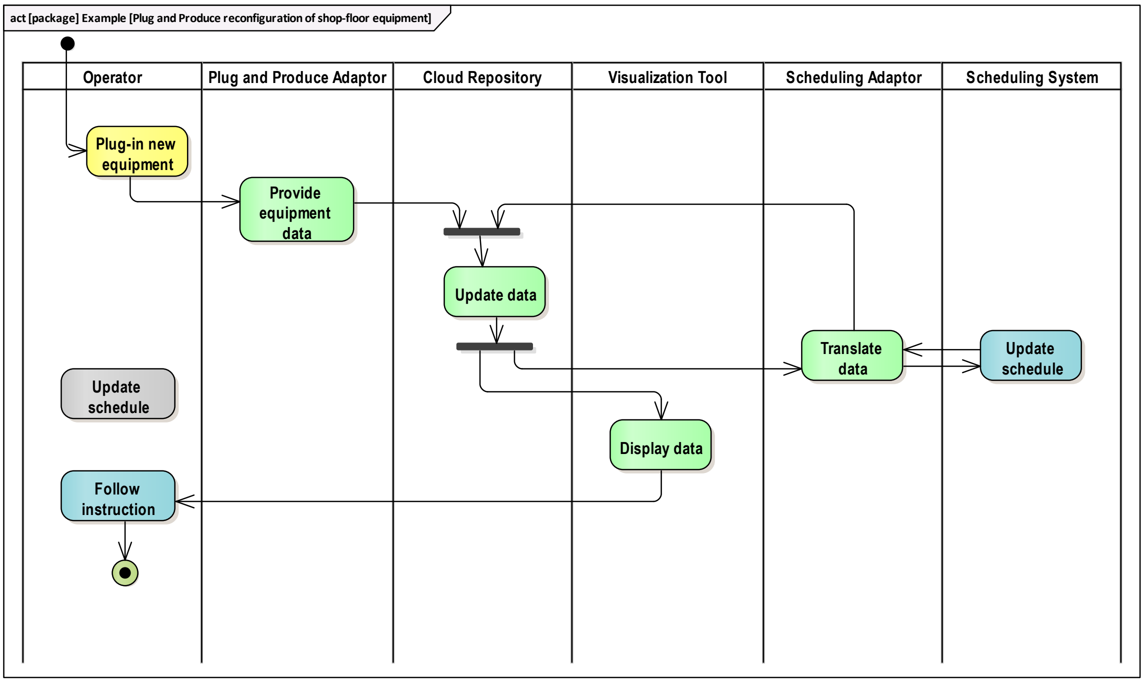


Figure 6-15 Example of Activity Diagram of the TO-BE situation

Eventually the same approach can be used also to evaluate different migration options by making a more concrete trade-off of solutions based on a preliminary evaluation of KPIs.

As shown in Figure 6-16, different IBDs, as well as ADs, can be modeled to better compare possible alternatives. After that, a qualitative evaluation of specific KPIs defined by the manufacturer can be represented using Block Definition Diagrams (BDDs), which basically represent the hierarchical structure of a system and its components. For example, the BDD in Figure 6-16 compares three different migration scenarios according to the following KPIs: productivity, downtime, and implementation costs.

In conclusion, although the use of SysML in this approach has been mainly conceived to support the Design phase of the migration process, these diagrams can provide a good basis already in the Preparation phase to describe the current situation of the production system and in the Option Investigation phase to holistically evaluate the migration alternatives under different aspects.

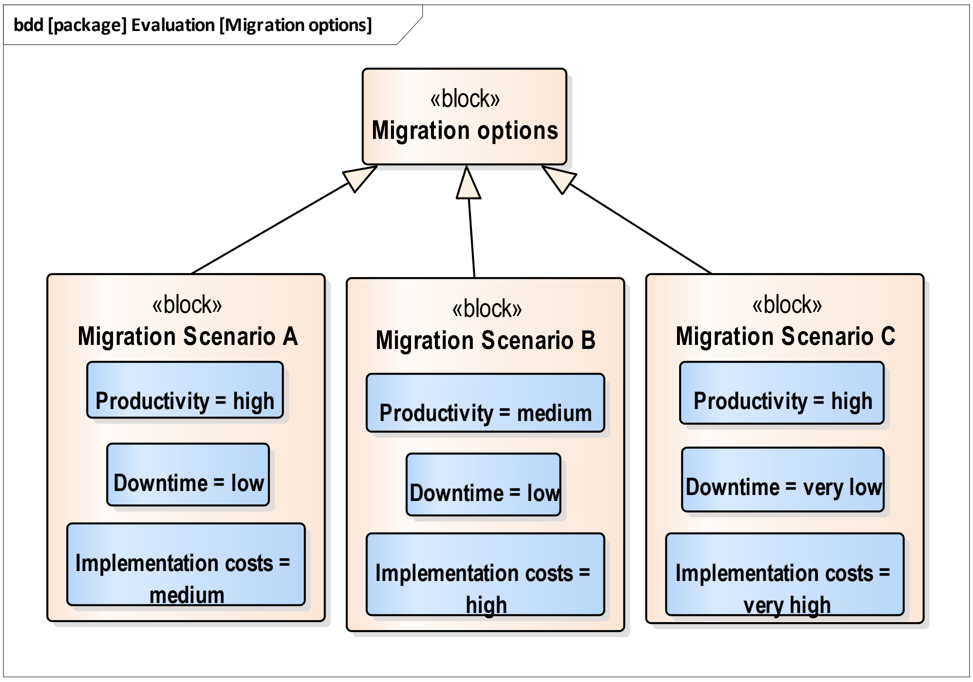


Figure 6-16 Example of Block Definition Diagram for the trade-off of migration options

The use of a color code, besides the SysML stereotypes, gives manufacturers a general but clear overview of the impact of changes implied by the new migration solution at technological, operational and human levels. Additional information can be assigned to the blocks to show some specific characteristics of legacy and new entities, needed to evaluate KPIs and impact aspects of each migration solution. The performance indicators related to the new systems are defined by the manufacturers and can be various, such as implementation time, systems integration, maintainability, IT security, costs of new technologies, return on investments, and others.

6.5 Summarizing the Holistic Migration Approach towards CPPS

According to the path logic defined in Chapter 6.2 the migration towards CPPS is a stepwise process leading to the continuous improvement of the factory by means of digitalization and robotization. The migration process defined in Chapter 6.3aims at performing each incremental migration step. The Preparation phase of the migration process leads to the identification of the business goals and the analysis of the current production systems, therefore it is supported by the Questionnaires. The questionnaires are used to conduct an interview with manufacturers in order to analyze the current strengths and weaknesses of the factory and identify room for business improvement. After this first analysis, in which also the initial goal of the migration is identified, a set of migration solution options are analyzed in the Options Investigation phase by representing them in the Migration Matrix. This phase goes a bit more into solution details identifying the impact of the solution at technical, operational and human dimensions. Based on the overview provided by the matrixes, one specific migration scenario is selected and specified in the Design phase with the support of Model-Based Design.

Table 6-6 describes how these methods and tools are correlated to each other and what their function in HoMoCPPS is.

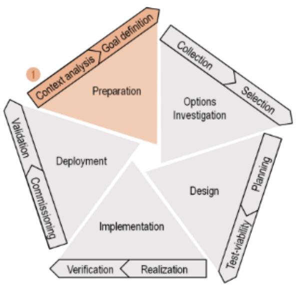
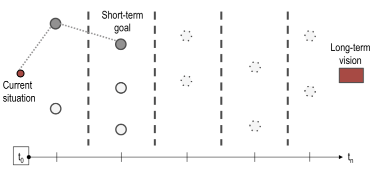
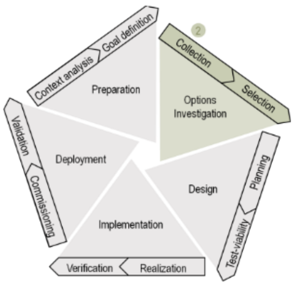
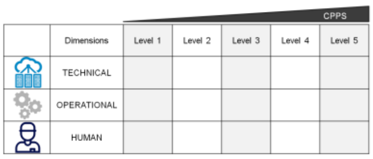
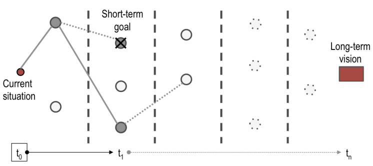
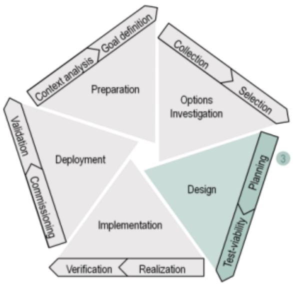
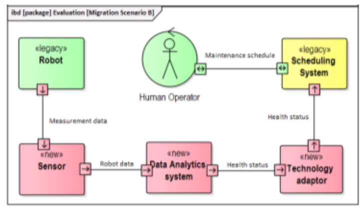
Migration definition path	Process phase	Method / Tool	Area
	Preparation 	Questionnaires 	Company
	Options Investigation 	Migration Matrix 	Migration scenarios
	Design 	Model-Based Design 	Specific solution

Table 6-6 Process support by methods and tools

This thesis does not define specific methods and tools for the following two phases of the migration process. However in [CaP18] and [PE18] a Petri Net application has been proposed to control the process, especially during the implementation and deployment phases.

7 Application of the holistic migration approach towards CPPS

The migration approach presented in the previous chapter has been developed iteratively by applying it to several industrial use cases within two European projects of the Horizon 2020 program: PERFoRM [PE15] and FAR-EDGE [FA16] projects aim at supporting manufacturers in decentralizing the control architecture to bring flexibility and reconfigurability of heterogeneous devices to their production systems.

While PERFoRM aims at the industrial implementation of the emergent approaches already developed in previous research projects by harmonizing them in an integrated solution, FAR-EDGE intends to overcome the limitation of these emergent approaches by introducing more innovative technologies, like Edge computing and Blockchain.

They both provide a distributed control architecture based on cyber-physical systems and internet of things technologies (with additional features), but they also apply the presented migration approach in order to guarantee a smooth and low-risk transition towards CPPS.

Several industrial use cases have been defined within the projects to demonstrate the benefits of the solutions developed in real industrial environment. The role of the presented migration process was to support the deployment of the projects' reference automation architecture in industry, ensuring a migration towards Industry 4.0 paradigm.

This chapter illustrates the application of the migration process' phases and the related methods and tools by using one specific industrial use case, already introduced in Chapter 1.2. Moreover, results from other use cases that applied the presented migration process are collected at the end of the chapter.

7.1 Application to a compressors manufacturing case study

The presented case study is here meant to show the procedure, used also for other industrial use cases, to apply the holistic migration approach developed to identify adequate migration steps towards CPPS. This chapter focuses on the execution of the first three phases of the migration process, which are the most critical of the migration approach as they define the goal of the migration and detail each migration step. Since the validation of solution system is very long and has not ended yet in the following industrial example, only a short outlook on the last two phases is provided.

As described in Chapter 1.2, this case concerns a traditional compressors manufacturing plant. The manufacturer aims at improving the current manufacturing process towards the production of small lot sizes of customized compressors by implementing the digital factory paradigms. The following sections describe in detail the phases of the migration approach performed in the framework of the PERFoRM EU project.

7.1.1 Preparation

The HoMoCPPS process starts with the preparation phase, which consists in the definition of the business long-term vision, i.e. the goal of the migration, and the analysis of the current situation of the production system.

The overall purpose of the preparation phase is to identify the first possible migration step towards the long-term vision of the company, thus the first short-term goal. In order to achieve this objective, the preparation phase is performed during an interview based on the assessment questionnaire. Additional open questions are explored in the same interview with focus to possible advantages and issues related to the implementation of CPPS in accordance with the business goals.

This phase involved different people from the following main organizational areas:

- Operational Technology Solutions (the key actor in this phase), i.e. experts responsible for deploying operational technology solutions (robots and machinery) and manufacturing processes;
- Manufacturing Information Technologies, i.e. experts responsible to the information technology systems related to the manufacturing of products;
- Factory Management, i.e. managers responsible for the overall factory in terms of goals, resource, and production value stream coordination.

The result of the first phase of the migration process is the assessment of the compressors manufacturing plant in terms of digital maturity at technical, operational and human dimensions. The interview has been conducted by the project’s consortium responsible for the migration process with the factory’s people mentioned above. The interviewers used the support of the assessment questionnaires described in Chapter 6.4.1 but without the pre-defined answers. The goal of the interview is to have more a discussion rather than a rigid fulfillment of the questionnaire in order to discover what is really important for the manufacturers and what are the weaknesses and strengths within the context of the factory.

After the interview, the collected information are compared by the interviewers with the pre-defined answers of the assessment questionnaire in order to give a digital maturity score to each question. The digital maturity indexes are identified at technical, operational and human dimensions of the factory, collected in a Microsoft Office Excel sheet, and represented in multidimensional radar charts from the overall maturity of the company down to each dimension and sub-dimension.

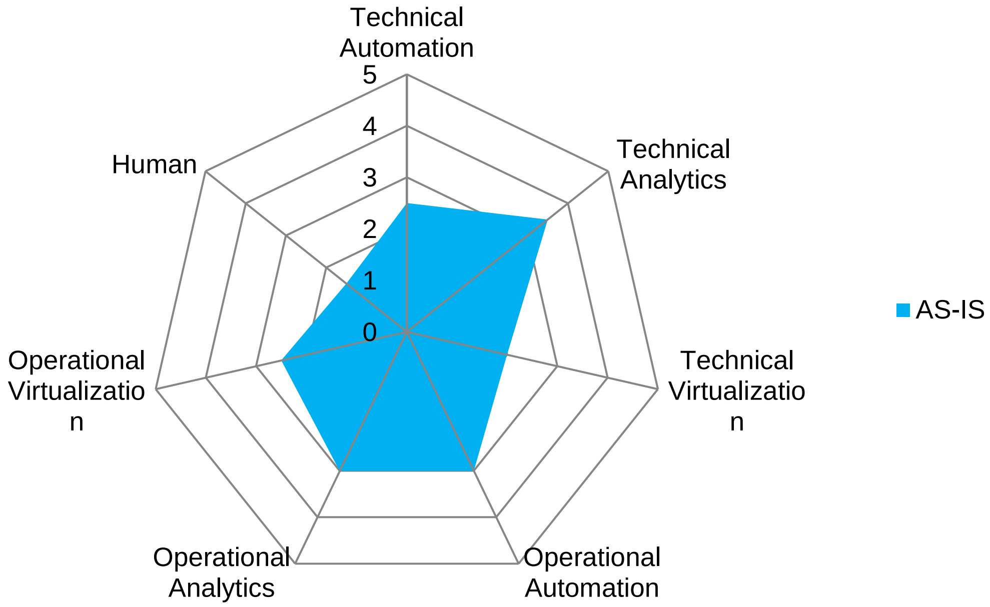


Figure 7-1 Radar chart of the overall digital maturity derived from the assessment questionnaire

Based on these results, strengths and weaknesses of the manufacturing plant are identified in order to build the Migration Matrix. As said, the answers collected during the interview are associated with a maturity level that can range from 1 to 5. In general the areas correspondent to a maturity level 1 or 2 are considered weaknesses, the areas with level 4 or 5 are considered strengths, while a maturity level 3 is evaluated as strength or weakness depending on the context.

These results are enriched with the manufacturers' comments about risks, obstacles, opportunities related to the implementation of CPPS in their production system according to their business goals.

The assessment questionnaire revealed the main weaknesses and strengths of the compressors manufacturing plant, which are summarized in Table 7-1.

The analysis of the assessment results shows on one side a good automation degree in terms of equipment and tangible assets available in the production process. The exchange of information is facilitated by a plant internal network using serial cable. On the other side the current centralized automation architecture does not adequately support the integration between shop floor and information systems. For example, the system can define the theoretical production capacity and update the actual production capacity with planned production losses and machines availability, but not with unexpected events.

Dimensions	Strengths	Weaknesses
Technical	• Automated equipment • Automated manufacturing data acquisition	• Centralized automation control • Maintenance monitoring • Machinery data acquisition
Operational	• Production planning and scheduling	• Maintenance planning • Simulation • Tracking and monitoring of products
Human	• Consolidated knowledge and experience about current machines	• Digital skills • I4.0 expertise • Guidelines • Training programs

Table 7-1 Assessment of the compressors manufacturing plant

The company has a good ability to automatically define, execute and control different production processes, such as production planning and quality control, avoiding manual and time-consuming activities. However, this does not apply to the maintenance engineering. A focused data analysis to understand possible trends and therefore prevent errors before they occur is not performed.

Moreover, the deployment of new applications by the automatic reconfiguration of physical equipment on different stations, according to the current operations, and its automatic synchronization among different information system requires to be improved. This issue can be solved by implementing a more decentralized and advanced automation control architecture that integrates automatically the shop floor and the IT systems to ensure the process parameters optimization as response to operational or business events. Related to the integration of shop floor and IT systems is the need for sensors and new IT infrastructures to collect, storage and prepare all the information available within the production plant in a specific data set.

Different human roles are involved in the production plant. The assessment particularly identified as main issue the lack of IT skills related to advanced Industry 4.0 technologies not supported by adequate internal training programs. Additional guidelines will be required by operators and engineers to deal with the next generation automation systems and related operations.

In addition to the assessment overview, risks and constraints have also been investigated during the interview. A very preliminary impact analysis highlighted risks related to system performance, implementation, maintenance, and organizational aspects. In particular, the insufficient acquisition of physical data from machinery, due to unavailable specific sensors, and the need of high skilled operators, as well as IT experts able to deal with the new automation architecture. Internal security policies need to be taken into account to meet special requirements related to the integration of new applications with legacy systems. To avoid production risks, the new technologies should be tested and verified in the real environment and data will be initially gathered only from an intermediary database, which collects data coming from the shop floor through legacy databases.

Regarding new technologies, the manufacturers see as a possible obstacle also the lack of support from technology providers and skills available on the market, which could prevent the continuity of use and user satisfaction. The human acceptance of the new system solution at global level from IT organization has also a big importance in the successfulness of CPS in industry. Like new resources, also new skills and competences would be necessary to use and maintain the CPPS systems.

As result of the preparation phase, the business long-term vision has been identified in increased product delivery reliability and ability to react to changes in customer demands. The main goal is thus to achieve an increased availability of production equipment along the whole value chain by preventing unplanned downtimes of machinery. To increase production flexibility and reconfigurability a link between industrial field devices and systems of the upper IT levels has to be established. Therefore, the first migration step should address solutions that enable a first decentralization of the control automation architecture towards a seamless communication among heterogeneous systems.

7.1.2 Options Investigation

The Migration Matrix enables the analysis of a migration scenario by identifying what entities are involved at technical, operational and human dimensions, and what is their maturity level with respect to the goal of digital factory. Taking into account the factory's strengths and weaknesses derived from the assessment questionnaire, a set of concrete migration solution is evaluated. In fact, the Migration Matrix provides a high-level view of what should be improved in the current production system and also suggests what steps can be considered to achieve the highest level of digital maturity.

Each migration scenario always has at least one component of each dimension. This is because only the maturity improvement should be considered at technical, operational and human dimensions of the factory in order to positively affect business value and enable the improvement process.

According to the outcome of the preparation phase, more precise tracking and monitoring of parts and semi-finished products as well as monitoring of production equipment was identified to be the first necessary step to increase availability and flexibility of the production system. Therefore, two main migration scenarios have been identified for the compressors manufacturing plant:

1. Improve maintenance planning system to reduce machining processes delays due to tool breaks;
2. Improve tracking and monitoring of product parts and production equipment to avoid assembly interruption and product buffering due to missing components.

The first scenario involves predictive maintenance technologies [HW11], which can help to optimize the whole production process and support the maintenance department [PE16b]. This implicates a condition monitoring system that calculates the condition of shop floor resources based on available inputs from different resources. Moreover, maintenance tasks have to be integrated into production scheduling for a better production planning. To enable this scenario machine data collection is a high priority feature that generates the database for the maintenance task creation.

The second scenario foresees the introduction of tracking and tracing technology to identify critical components and its position along the product lifecycle. Using the event processing of items, the tracking and tracing technology can be applied for decision-making and optimization processes. Moreover, a Cloud level within a distributed automation architecture can collect and make available tracking results of production equipment and product data in real-time among different applications to enhance production flexibility when any change occurs.

These solutions are investigated according to their feasibility in the considered production systems, thus, based on the presence of barriers or lack of resources to enable the migration towards a digital solution [PE16b]. The migration matrix supports the manufacturer to understand if the proposed solution is feasible or unfeasible according to its positive and/or negative impact on the existing production environment. In the end the manufacturer selects a scenario comparing the correspondent migration matrixes and considering the envisioned risks, obstacles and opportunities.

	Level 1	Level 2	Level 3	Level 4	Level 5
	Control automation architecture				
	Not available	Centralized and monolithic	Centralized but modular based	Decentralized, each automation process is self-contained	Decentralized and based on service-oriented principles
	Equipment / machinery connectivity and communication protocols				
	Not available	Basic connectivity	Local network (LAN/WAN)	Networked with vendor specific API	Networked with I4.0 standard communication protocols
	Error monitoring				
	Not available	External monitoring devices (per equipment)	Centrally available through SCADA	Centrally available and analyzed through MES	Fully available ad analyzed through the Cloud
	Systems for predictive maintenance				
	Not available	Manual process defined by human auditing	Manual process based on some monitoring data	Predictive maintenance based on monitoring data	Fully automated predictive maintenance process in the Cloud
	Equipment data management				
	Manual	Locally managed at machine level (PLC)	Centrally managed from SCADA	Centrally managed by MES	Centrally managed according to ERP
	Maintenance scheduling				
	Manual, when necessary	Manual, based on machinery instructions	Manual, based also on historical data	Automatic, using quantitative tools	Preventive, based on real-time production data
	Failure analysis				
	Not available	Only occasionally	Standard practices for problem monitoring	Standard practices for root causes identification	Standard practices for continuous improvement
	IT Operator				
	Not available	External service provider	Internal for traditional IT systems	Internal for specific digital systems	Internal for all systems from Field to Cloud
	Industry 4.0 / digital technologies skills				
	No experience in digital technologies	Little experience in digital technologies	Digital skills in some technology focused areas	Digital skills in most business areas	Digital skills all across the business
	Impact on employees				
	Still unclear	Identified in general terms	Analyzed	Defined	Implemented in continuous improvement

Table 7-2 Excerpt of the Migration Matrix of the first migration scenario

Since compressors manufacturers give high importance to quick results, the priority has been given to the machining processes in the pre-fabrication phase, i.e. the manufacturing of stators and rotors of the compressors, to which the first migration scenario (represented by the Migration Matrix in Table 7-2) is applicable.

The Migration Matrix represents the main weakness of those technical, operational and human aspects that need to improve, in the selected migration scenario, towards a higher digital maturity level in order to move towards the CPPS vision. In Table 7-2 are reported only the most critical aspects evaluated after the interview. The main technical aspects identified are: the control automation architecture, equipment connectivity and communication protocols, error monitoring systems, and predictive maintenance. Some operational and human aspects are linked to these technologies, i.e. equipment data acquisition and management, maintenance planning and scheduling, failure analysis, and all the employees involved in the selected migration scenario, especially the IT operator.

Since the migration of the compressors manufacturing plant has been studied within the PERFoRM project, the target of the TO-BE situation was the decentralization of the current automation architecture. In fact, the distributed PERFoRM reference architecture based on service-oriented principles enables the further continuous improvement in the direction of flexible and reconfigurable production system and, thus, ensures the effective transformation to the Industry 4.0 and Digital Factory paradigms.

In order to implement the PERFoRM reference architecture (Figure 7-2), advanced information and communication technologies are required, such as a common middleware with standard communication protocols and interfaces, to enable the integration of heterogeneous system components. In fact, the intention for the first migration step is to maintain some of the legacy components in place, which will be connected to the new components.

According to the results of the assessment questionnaire system maintenance, scheduling and planning technologies as well as the error detection technologies need to be upgraded with additional technological solutions. Therefore, besides the automation control architecture, new data analytics tools, as well as scheduling and simulation tools have been investigated. Data analytics applications have been investigated to gather data from databases and machines and to analyze machine alarms and production data trends to improve the maintenance planning.

An important aspect to be taken into account is the data acquisition and communication availability within the company’s internal network and the integration of the new tools with the legacy applications environment for scheduling and maintenance operations. To this end, standard interfaces and wrappers are mandatory to translate system data in a common language and enable data exchange.

The first migration step does not only aim at starting the transformation of the current production system into a CPPS but also at providing added value.

In conclusion, while in the preparation phase the business long-term vision has been identified in increased product delivery reliability of production machinery, the first short-term goal recognized within the options investigation phase is to prevent unplanned downtimes of machinery by means of Industry 4.0 technologies. In particular, through an improved monitoring of the equipment status and a better maintenance planning and scheduling of activities, the selected solution will:

- Increase machine availability through improved condition knowledge and maintenance activities;
- Better plan and schedule necessary downtimes of machinery for maintenance in order to reduce negative impacts on production entities.

7.1.3 Design

The solution identified within the PERFoRM project addresses flexibility and reconfigurability through a decentralized automation control architecture, which can also support the integration between production and maintenance planning based on machinery status data. This link is enabled by the application of service-oriented principles to a decentralized automation control architecture, which establishes the communication and integration of heterogeneous hardware devices and software application of an ecosystem.

The PERFoRM reference architecture integrates different levels of the ISA-95 automation pyramid by using a distributed service-based integration layer, i.e. an industrial middleware, with service technologies. Systems of different nature can be integrated through a standard communication protocol (the PERFoRMML) and standard interfaces or technology adaptors, for PERFoRMML-compliant systems or legacy systems respectively.

The figure below represents the overall PERFoRM architecture in which the tools developed within the project can interact via standard interfaces for services through the middleware with the legacy systems, integrated to the architecture with the support of specific technology adaptors and wrappers. The architecture functionality is not limited to the represented components, but it can be extended also to other possible new tools or legacy systems, which can be connected to the Middleware by using, respectively, standard interfaces or new technology adaptors that expose their data in a PERFoRM-compliant manner. The functionalities of the PERFoRM reference architecture are detailed in [Le16], [Go17]and [Go17].

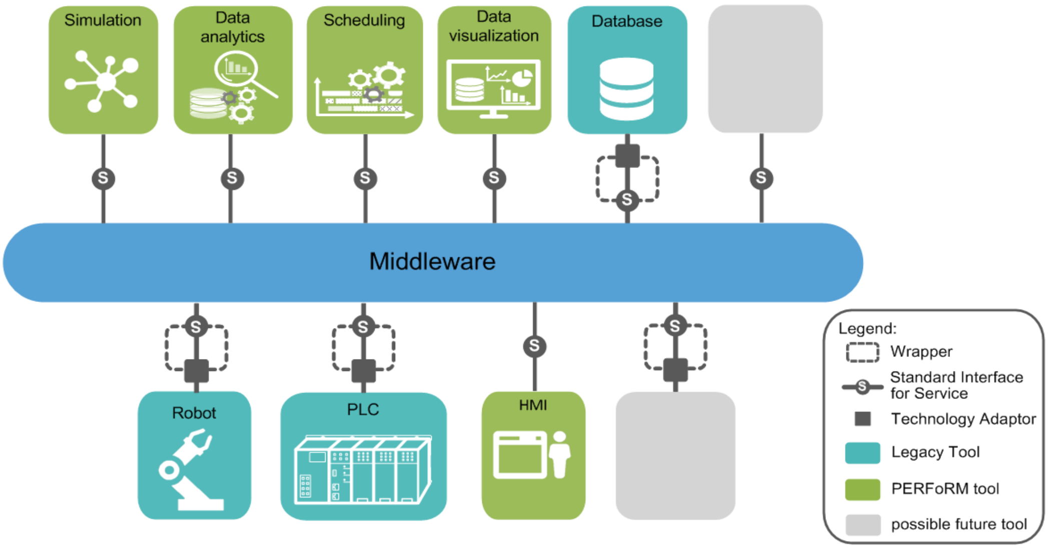


Figure 7-2 PERFoRM reference architecture

The selected migration scenario of the compressors manufacturing plant concerns data analysis, manufacturing acquisition systems functionalities and the ability to adjust maintenance scheduling processes. According to the results of the previous phases, the system maintenance, scheduling and planning technologies need to be upgraded with additional technological solutions. The PERFoRM reference architecture is applied to enable the communication and integration of heterogeneous entities, which have been identified in the specific migration scenario as following:

- Machines
- Production data acquisition system
- Production scheduling system
- Maintenance ticketing terminal
- Scheduling database
- Maintenance database
- Planning department
- Production department
- Maintenance department

In the AS-IS situation machines' maintenance tasks are defined by the machine supplier and stored in a maintenance database in which all maintenance data are collected. These tasks are manually integrated with the production tasks in the production scheduling system, generating manufacturing schedules that are stored in the database for production data and manufacturing schedules. This database receives the machines' production data via a production data acquisition system. The systems are connected via a TCP/IP (Transmission Control Protocol / Internet Protocol) network, which is not connected to the manufacturing network. Maintenance tasks are manually integrated in the production planning, according to machine supplier's instructions, by the planning and maintenance departments together. In case of repair activities, the maintenance is requested by the production operator as soon as he detects a machine failure. Maintenance tasks are then prioritized based on the type of issue.

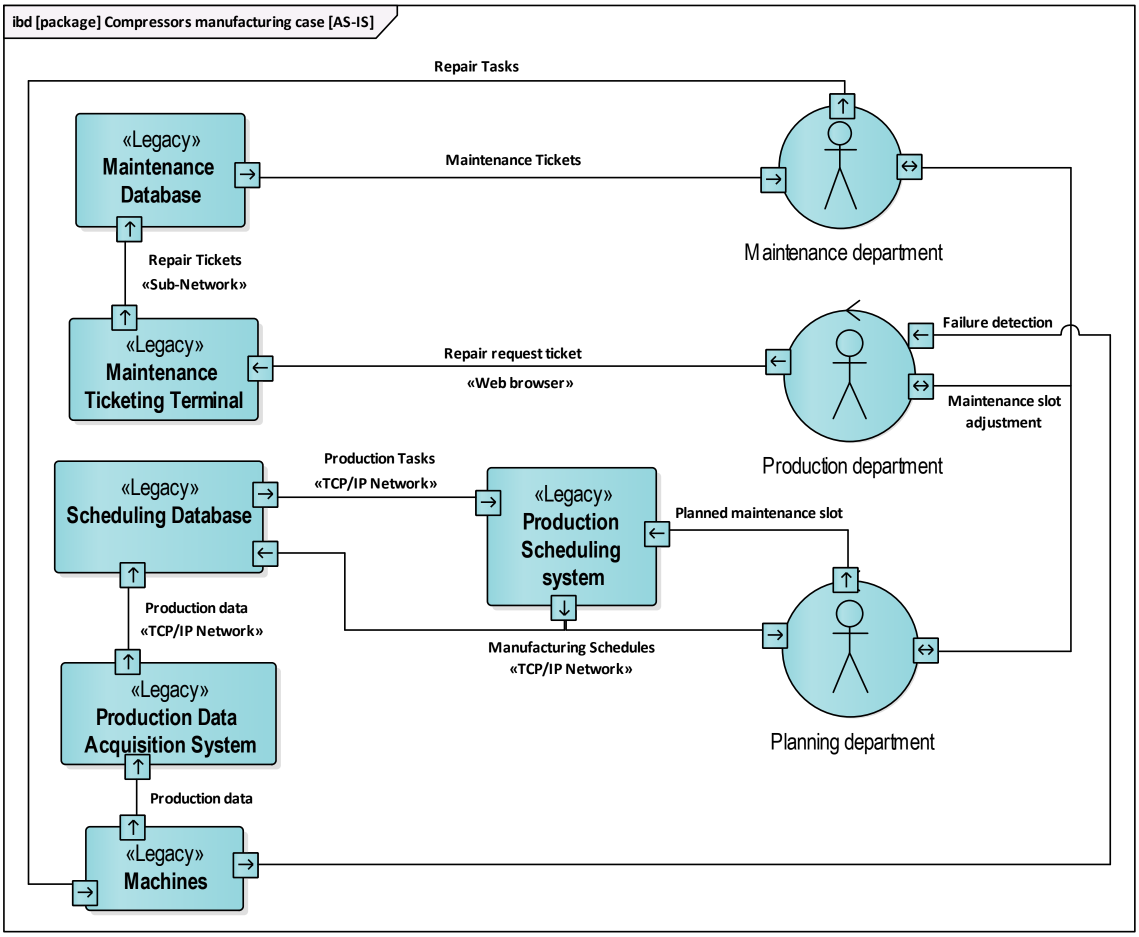


Figure 7-3 Internal Block Diagram of the AS-IS situation

The Internal Block Diagram depicted in Figure 7-3 represents the legacy entities involved in the AS-IS situation described above as blocks with the <<Legacy>> stereotype. Flow ports and connectors represent the interfaces and information exchange of the legacy entities to perform the AS-IS maintenance scheduling process, which is detailed in the Activity Diagram in Figure 7-4.

From the assessment of the migration opportunities emerged that new manufacturing computerized system technologies will improve the current production scheduling, together with the introduction of machine breakdown prediction technologies, human-machine interaction technologies and system communication protocols and interfaces.

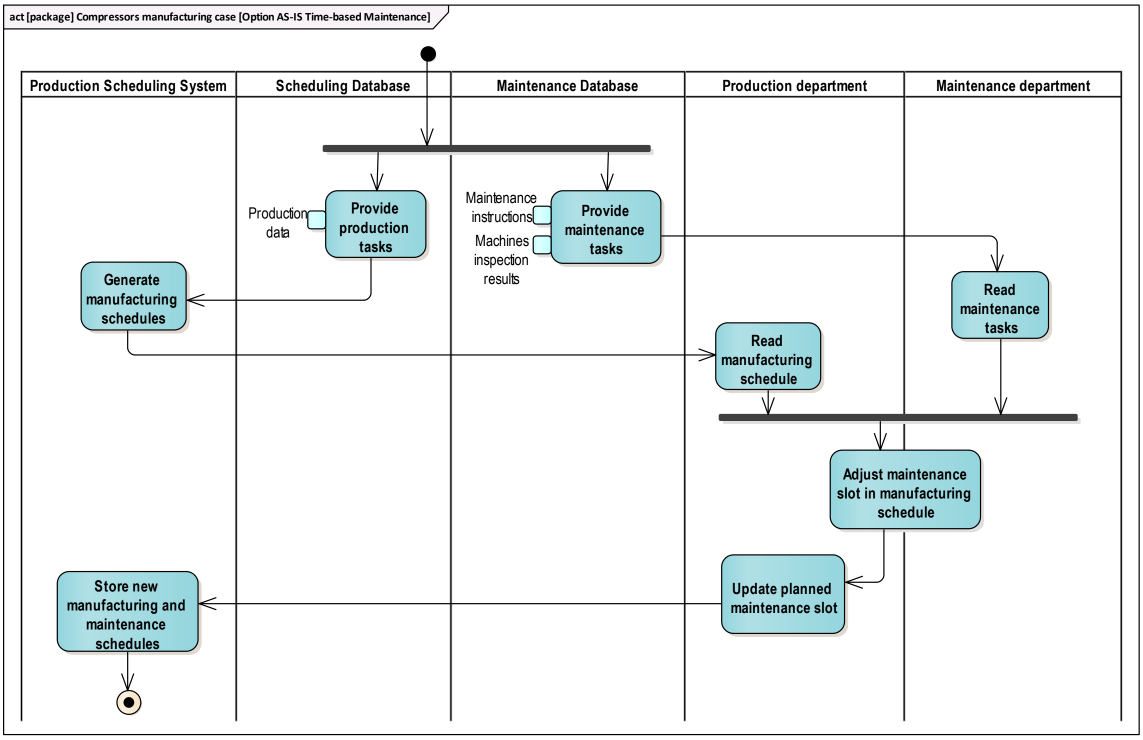


Figure 7-4 Activity Diagram of the AS-IS situation

Therefore the TO-BE condition concerns the ability to prevent machine breakdowns and downtimes through improved production monitoring systems, i.e. predictive maintenance and system scheduling and planning technologies supported by new simulation tools. The solution that enables the TO-BE vision is detailed within the design phase to identify new system components and specify the interfaces of the system devices and applications. The new software applications are various but already connected through the new automation architecture, while the legacy database systems need to be provided with additional connectors in order to be able to exchange data with the other systems.

Within this phase, the impact aspects related to the integration of the new system with the legacy ones are highlighted by means of SysML diagrams. The selected solution for this application case is depicted in Figure 7-5, in which the stereotype <<PERFoRM>> characterizes the new components developed within the project for the target solution.

The TO-BE system integrates new applications developed within PERFoRM and legacy systems through the industrial middleware, standard interfaces and technology adaptors. The data analytics is performed by three different applications (i.e. Bayesian diagnostic and prognostic, data mining and min-max toolbox), which collect data regarding maintenance tasks, production tasks, machine alarms and machine data from the databases through adaptors and directly from the machine through sensors. These tools generate machine data change and alarm trends that are sent to the maintenance task edition and the selection scheduling tool through the industrial middleware and via the standard PERFoRMML protocol. Through the selection scheduling tool the planning department is able to change maintenance tasks and select the best scheduling based on the data trends and the KPIs evaluation displayed in the interface. The KPIs are evaluated by a new dedicated simulation tool based on the schedules generated by the scheduling tool, which can now receive both maintenance and production tasks from the legacy databases through technology adaptors.

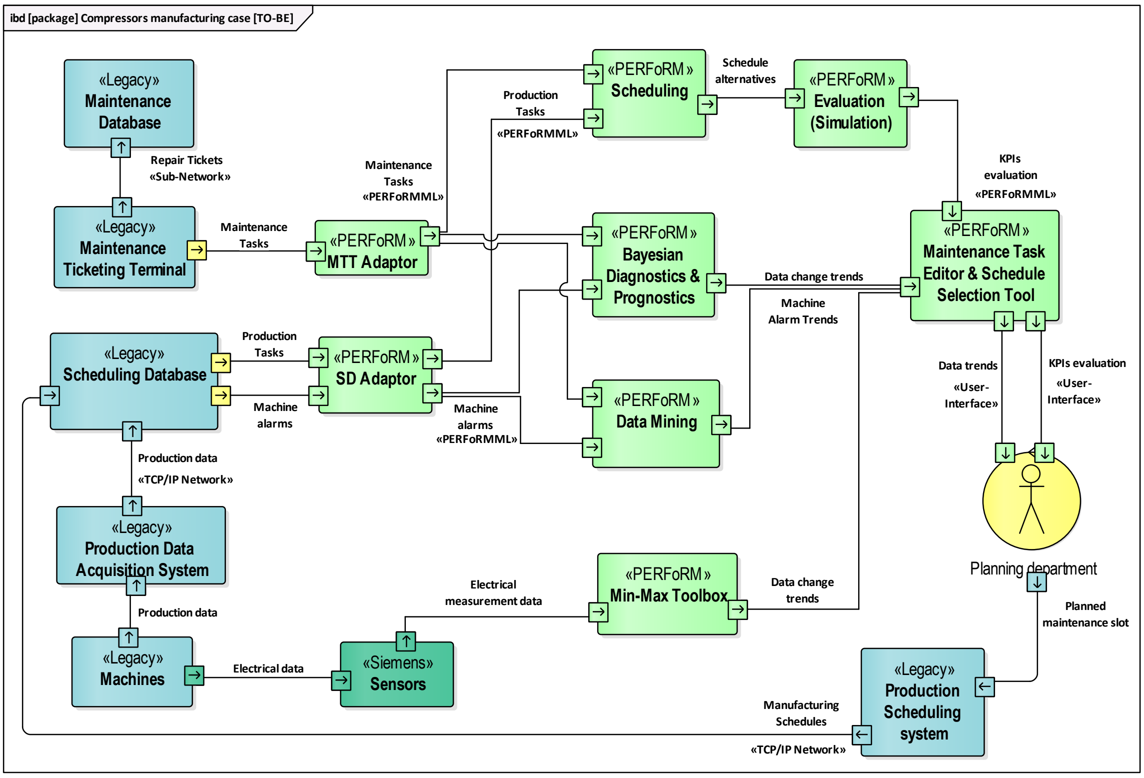


Figure 7-5 Internal Block Diagram of the TO-BE situation

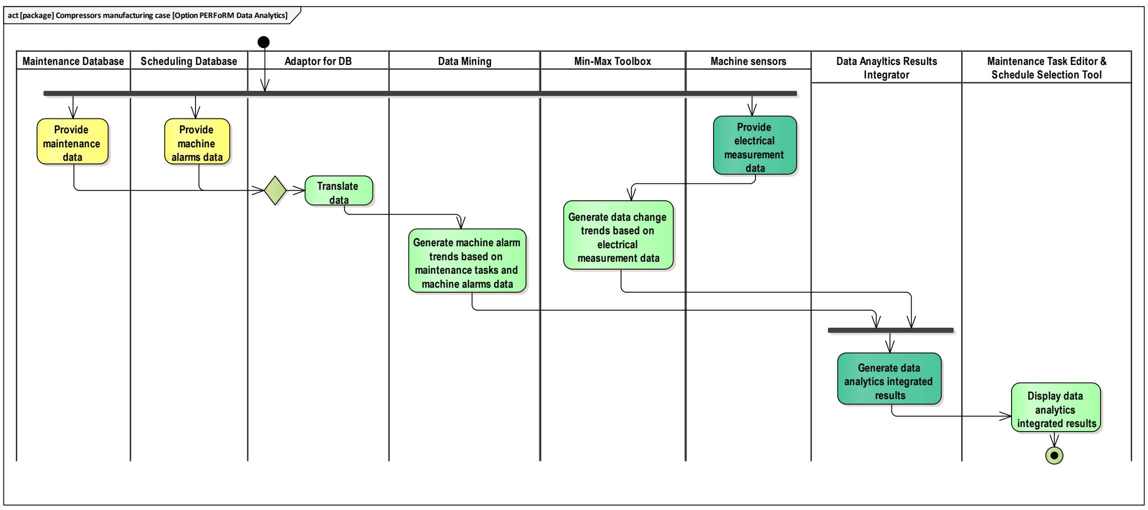


Figure 7-6 Activity Diagram of the TO-BE Data Analytics

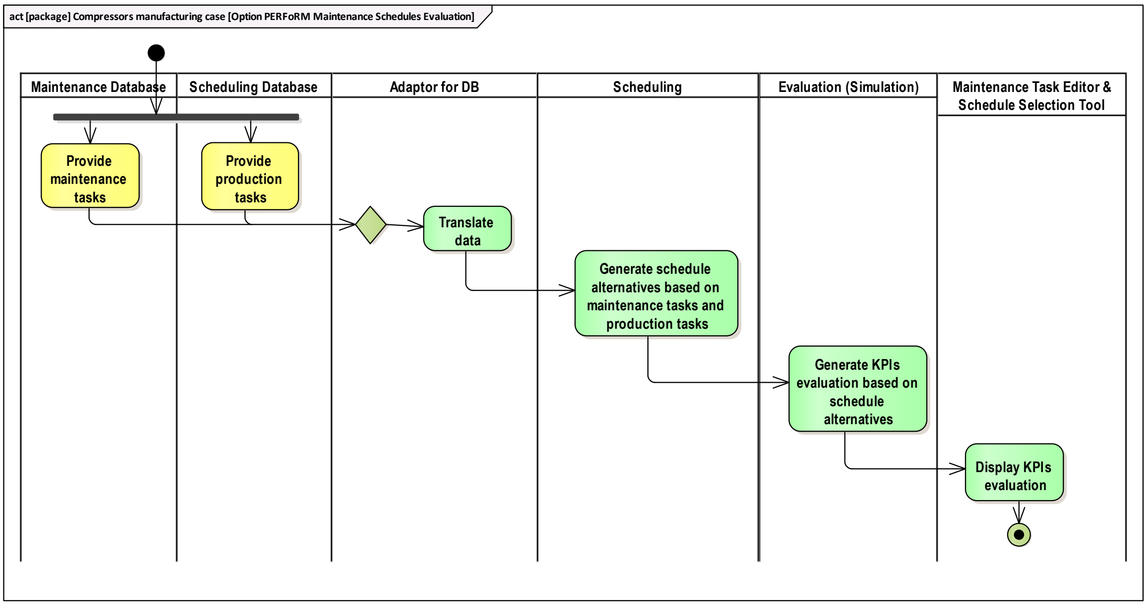


Figure 7-7 Activity Diagram of the TO-BE Maintenance Schedule Evaluation

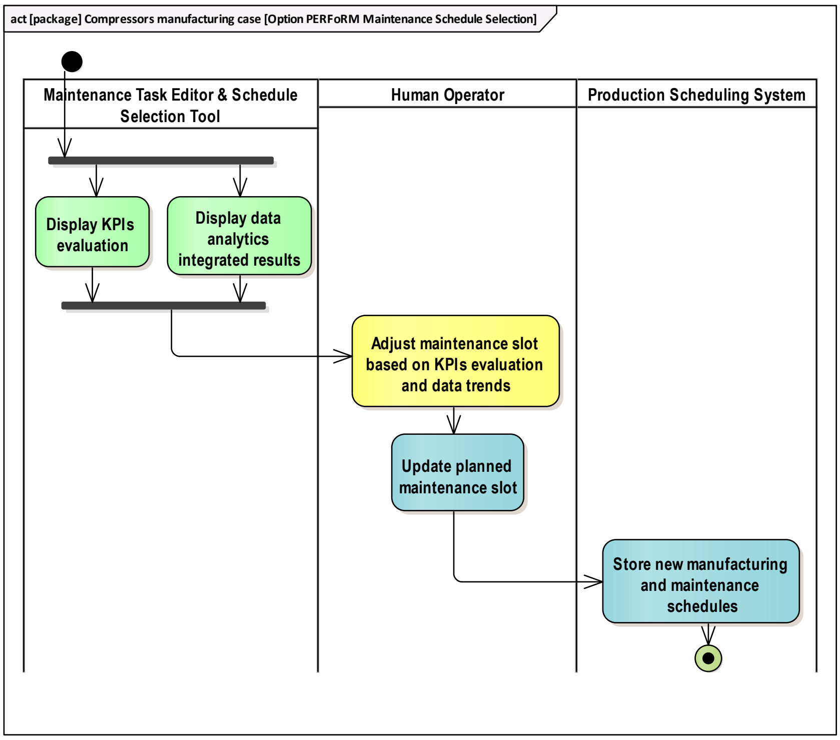


Figure 7-8 Activity Diagram of the TO-BE Maintenance Schedule Selection

The Internal Block Diagram in Figure 7-5 depicts the new components developed in PERFoRM in green, while in yellow the legacy entities impacted by the new systems. Since the TO-BE solution concerns the integration of new and legacy systems through the PERFoRM middleware, the legacy databases required adequate technology adaptors to be PERFoRMML-compliant and provide data to the new application. Therefore, the output flowports of the maintenance ticketing terminal and production scheduling database are colored in yellow. The connectors between blocks also show the new stereotype <<PERFoRMML>> that indicates the new communication protocol adopted in the TO-BE situation to enable the exchange of data and information through the new distributed automation architecture.

Although these legacy systems physically remain the same, they need to provide different data in a different way. The operational change is depicted in the Activity Diagrams. The TO-BE activities are split in three diagrams: Figure 7-6 represents the data analytics, Figure 7-7 depicts the maintenance schedule evaluation, and Figure 7-8 shows the maintenance schedule selection.

For example, the databases provides new data required by the data mining (in Figure 7-6) and by the scheduling system (in Figure 7-8), which are actions depicted in yellow.

Also the human operator is impacted by the new systems since he changes his tasks related to the definition of the maintenance schedules. While in the AS-IS situation the allocation of the maintenance tasks in the production scheduling is defined manually based on a maintenance and planning departments' negotiation, in the TO-BE situation is only the planning department that adjust the maintenance schedule based on algorithm data provided by the new analytics tools. As depicted in Figure 7-7 the human operator adjusts maintenance slot based on the information provided by the new data analytics tools through the maintenance task edition and schedule selection tool. Then he updates the planned maintenance slot in the legacy production scheduling system as in the AS-IS situation.

The designed solution will change the current maintenance planning in terms of way of working by reducing human error, improving quality and maximizing speed of processes. Although less people will be involved in the definition of maintenance plan, operators perceive this change not as a replacement of their workforce but more as opportunity to improve their work routine with the help of smart technologies. In fact, to a more general extent, digital systems will assist current human operations rather than completely substitute operators [UC18].

7.1.4 Implementation and Deployment

The successive phases of the migration process concern the realization of the designed solution components, their verification and validation after deployed in the production system.

To mitigate risks and avoid systems' performance failures a Parallel Implementation strategy has been chosen. Since both systems will run together, the occurrence of problems in the target system (running as slave) is mitigated by the use of the old system and provides a safer period of time to correct its behavior. In this case the scheduling of the maintenance operations will be performed by using both the old and the new system until the target solution is validated and can replace the legacy workflow. This approach also allows maintaining the current human workforce at the production and maintenance departments, which will be gradually trained on the new system while still using the old one.

In the first implementation of the PERFoRM solution the legacy systems are connected to the new middleware and applications through the manufacturing local area network. This risk mitigation measure is taken to prevent unintended interferences with the factory system. Therefore, necessary data flows from the new PERFoRM systems to the legacy ones are done manually.

The new IT components of the PERFoRM reference architecture (middleware and services) are hosted on a dedicated hardware within the factory, i.e. a standard PC. Depending on the performance requirements of the several services, it is possible that during the implementation and testing this concept is enhanced to host middleware and services on different hardware, which are then connected through a standard network, i.e. no difference for the service implementations due to the middleware approach (services are always communicating through network/middleware). In addition to the PC-hosted tools/services, the new Min-Max-Toolbox system is implemented using dedicated hardware (Microcomputer Units, Sensors) which are mounted directly in the cabinets of the pre-fabrication machines considered for the use case.

The deployment of the new automation solution in the production system requires digital skills related to the use of the PERFoRM software applications and the maintenance of the architecture with its standard interfaces. Although the training is not expected to be a critical activity during the migration process in this case, some roles will need to be skilled up. In particular, the IT developer should be trained to deal with the new automation architecture, while the production operator will learn how to use the new interface to select and adjust maintenance schedules in the production plan.

The solution will be finally validated according to the flexibility requirements addressed by the manufacturers within PERFoRM:

- Reduced delay times which are due to machine breakdowns
- Reduced downtimes of the machines
- Improved quality and reliability of the machining processes
- Moving from a fixed scheduled and mostly reaction based maintenance system to dynamic maintenance system.

In case the requirements will be fully validated after the deployment phase, the new solution will stay in place providing a higher digital maturity to the production system. Comparing the TO-BE situation with the AS-IS condition in the radar chart the considered production system will have a decentralized control automation architecture based on service-oriented principles, in which some of the production systems are connected via an Industry 4.0 communication protocol. Systems for predictive maintenance will be based on production data monitoring and errors are monitored centrally through the new data analytics applications that automatically elaborate maintenance scheduling based on data trends. By means of sensors and data analytics will be also possible to analyze failures identifying the root causes. Also current employees will have higher digital skills through adequate training programs, especially to deal with the new service-based automation architecture.

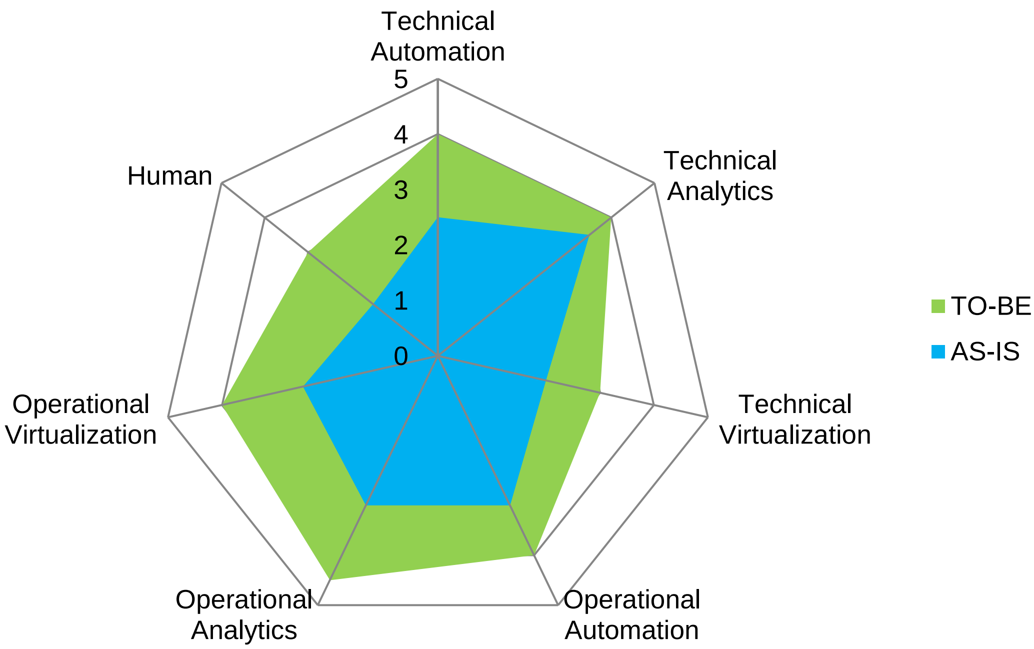


Figure 7-9 Radar chart of the expected overall digital maturity in the TO-BE situation

The solution implemented in PERFoRM represents only the first migration step, therefore the highest level of digital maturity is not yet achieved. However, the radar chart shows a general improvement of the production system at technical, operational and human dimensions of the factory in the direction of CPPS.

The deployment of middleware and standard communication protocols to all systems and application will improve flexibility and reconfigurability of the manufacturing plant. Also the implementation of predictive maintenance, tracking systems, and other next generation systems will enhance the digital maturity of the compressors production system. Therefore, the migration process should be performed again from the beginning in order to identify and implement the next migration step towards CPPS.

7.2 Results from industrial implementation

The implementation of HoMoCPPS has been applied to the compressors manufacturing plant in Siemens AG, i.e. the case study presented in Chapter 7.1, but also in various other industrial environments, such as the Volvo assembly line of heavy duty trucks, the Whirlpool production of cook tops, and IFEVS manufacturing of micro-electrical vehicles. The case studies results and manufacturers feedback are taken as basis to validate the proposed migration process.

The production systems considered in the case studies differ in terms of size, produced volume, product variety and complexity, and also digital maturity (Figure 7-10).

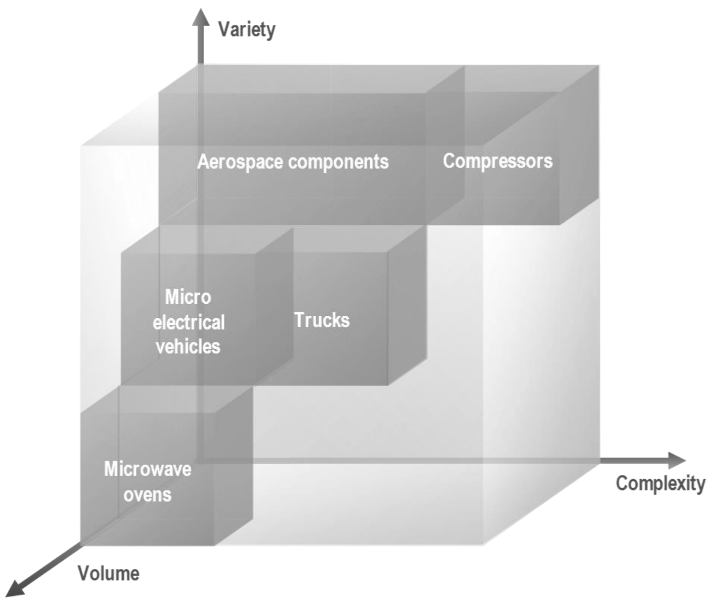


Figure 7-10 Application in industrial use cases (adapted from [CaF16])

Usually large companies have a hierarchical organizational structure in which employees work in silos without having a comprehensive business overview, while small companies have a flatter management making easier the direct interaction with decision makers. For small enterprises every decision taken could be very risky due to the high costs involved and their limited financial resource. By contrast, big companies tend to be more conservative and care for their existing customers by invest their money to improve only what is already in place.

These differences are reflected also in the application of the migration approach. On one hand, the Options Investigation phase can be very long and difficult for green-field applications. High uncertainty on how to achieve the long-term goals and a low number of legacy system drives to a wide range of possible migration solutions, however the limited financial resource need also to be taken into account. In case of larger companies the same phase can be different, since they usually already have a clearer idea on which production operations and systems need more improvement. The selection of the migration option is driven by internal company policies, constraints and the availability of own new technologies. In the extreme case of a very large number of boundaries, the migration could be not possible at all. The migration matrix was a very helpful tool to analyze and narrow the migration solution space towards a specific short-term goal according to the current digital maturity level and main strengths and weaknesses of the factory derived from the assessment questionnaire. In the case study described in Chapter 7.1 the preparation and options investigation phases proved to be helpful in the selection of the short-term goal and identification of the optimal migration step towards the long-term vision, based on the system's constraints in the project.

The Design phase can be longer in older companies, compared to small enterprises, due to the existence of several legacy devices and application that need to be integrated with the new systems and communication network. The case studies derived different solutions, even though all based on a decentralized control automation architecture. Usually the number of legacy systems kept in the new solution is higher in case of big companies rather than small ones. This also depends on the production area in which the manufacturer intend to start the migration.

As seen in Chapter 7.1, the model-based systems engineering approach and the representation in SysML of the new solution components proved to be beneficial to depict their impact of change on the legacy systems and the changed workflow, adapted to the new solution. Of course, a more detailed design of the solution must follow by using adequate tools, according to the specific solution.

Implementation and deployment phases then depend very much on the designed solution and the requirements and KPIs selected to evaluate the system's feasibility and reliability in a production system. The three implementation strategies for migration identified in the literature provided an indication to realize and deploy the new solution in the legacy production systems. However these two phases have not been completed yet in the application use cases, so the results cannot be fully evaluated.

In addition, the presented migration approach has been applied as support for product developers that intend to provide customers also with a roadmap to implement their innovative product in an existing production system. In addition, they can use the approach to show the value add of different solutions to the customer's production system. In this case, the methods and tools developed for the migration process are used with a slightly different purpose: the migration matrix is used to show how the developed solution can improve and increase the digital maturity of a manufacturing system; while the SysML diagrams that represent different integration options of the solution are collected in a library, ready to be used as implementation blueprints.

In conclusion, the necessity of a stepwise holistic migration approach towards the cyber-physical production systems became clear in all case studies. The presented migration approach has been proven as very useful since it represents a good and structured guide to identify step-by-step the appropriate target solution. Moreover, the different implementation cases revealed the process wide-range of applicability to different manufacturing environments, both from plant manufacturer and solution provider perspectives.

8 Summary and Outlook

The upcoming fourth industrial revolution forces manufacturers to enhance their current production systems with new digital technologies in order to stay competitive in the market. Since technology innovation is growing fast while its industrial deployment is still very low, the main challenge is to understand the positive and negative impact of these innovative solutions to the legacy production environment. Manufacturers need to be guided in their digital transformation identifying a suitable migration strategy in order to avoid implementing solutions that can turn into a waste of time and money.

This thesis presented a stepwise and holistic approach tailored to the migration of legacy automation systems towards cyber-physical production systems of Industry 4.0 paradigm.

After discussing how the production systems are changing with regard to the fourth industrial revolution, especially in terms of automation architecture, and what this change could impact within a factory, a set of required characteristics for a migration process has been derived in Chapter 2.4.

Based on these requirements, a review of literature on existing migration strategies and processes has followed in Chapter 3. These migration strategies refer to general implementation approach mainly adopted in informatics while the migration processes are stepwise procedures to transform an existing system into a new one developed in previous research. The comparison of migration processes with the above mentioned requirements shown in particular the lack of procedures supporting the analysis of a non well-defined target solution and the evaluation of migration alternatives.

The engineering practices described in Chapter 4, i.e. the philosophies of lean and agile approach, maturity model and model-based systems engineering, have been considered as additional procedures that can be integrated in a migration process in order to fulfill all requirements.

From the analysis of the state-of-the-art a gap with respect to supporting manufacturers in the migration towards the next generation of digitalized production systems has been shown in the following Chapter 5, which also details the main research question: *"How to derive migration strategies towards Cyber-Physical Production Systems?"*.

In the following, the derived three research questions are answered.

RQ1: *What approach can mitigate the introduction of digitalization and robotization in manufacturing domain?*

Manufacturers are not confident in deploying brand new technologies in their existing production systems since they do not have complete evidence of their benefit due to the lack of experience. The concepts of Industry 4.0 and cyber-physical production systems are still very fuzzy.

For this reason most manufacturers still do not comprehend the value of “digitalization” and its distinction from their current information, communication and automation technologies. Moreover, they need to ensure productivity to keep their current customers and safeguard their investments on production infrastructures.

Conversely, the introduction of digitalization and robotization in manufacturing should be driven by a change in the business strategy. In literature, no adequate guidelines or approaches have been defined to migrate a system while mitigating possible risks and amplifying benefits. However, the migration path definition logic described in Chapter 6.2 aims at introducing these technologies in a continuous improvement vision, representing a stepwise approach that aims at breaking down the uncertain path towards a long-term vision in intermediate short-term goals. This approach can provide manufacturers with small incremental improvements towards “digitalization” by implementing the next generation technologies step-by-step and evaluating their benefits at each migration step in a lean and agile fashion.

RQ2: *What process can support manufacturers to migrate towards Cyber-Physical Production Systems?*

The migration of existing production systems into CPPS should be guided by a sequence of procedural steps, like in every engineering project. A defined process provide a valid support to the user since it indicates what tasks should be performed and in which order. The migration towards CPPS is not only an implementation of a new technology but consists in the definition of a strategic solution that can support manufacturers in transforming their production system following an optimal migration path.

The processes analyzed in Chapter 3.2 are not adequate to support the migration towards the next manufacturing paradigm since they target a very specific technology and do not give room to other possible hybrid solutions to mitigate costs and risks. The 5-phase migration process presented in Chapter 6.3 provides guidance to manufacturers to analyze the long-term vision, identify a short-term goal, investigate possible options and design a solution for each migration step. The process aims at analyzing the current situation and the target vision in the first phase, at the beginning of each migration step, in order to re-evaluate the possible options and their impact based on the new condition of the production process achieved in the previous migration step. Therefore, the sequence of phases supports manufacturers at keeping in mind all the required aspects to be considered during the definition of a migration strategy.

RQ3: *What methods and tools can enhance the investigation of different migration alternatives?*

Methods and tools are fundamental to enhance the stability of the process and the traceability of alternative solutions to perform a migration step. Migration alternatives should be investigated among the available technology options on the basis of their impact on the existing production system, their benefit, and their feasibility. Through the use of defined methods and tools the communication between decision-makers and even the decision-making process itself can be improved.

Based on the analyzed engineering practices, this thesis proposes in Chapter 6.4 three methods or tools to enhance the investigation and design of migration alternatives before the implementation of a solution:

- the assessment questionnaire – to assess the current situation of a company at technical, operational and human dimensions in order to identify where there is potential of improvement, taking into account obstacles and constraints;
- the migration matrix – to analyze the applicability of available Industry 4.0 technology options to the considered production system and evaluate them on the basis of manufacturer's priorities, criticalities, and desired benefit;
- the MBSE approach with the SysML language – to model and graphically represent how the selected solution impacts on the legacy systems and human entities in order to understand if the solution is feasible and what further aspects must be considered in the implementation and deployment phases.

Compared to other approaches, the presented migration process fulfills all these requirements defined in Chapter 2.4: stepwise, iterative, incremental, holistic, include options, and agile.

HoMoCPPS is a stepwise approach based on the definition of incremental migration steps in which digital technologies are introduced in existing production systems towards the transformation into CPPS. The proposed migration process defines five phases to iteratively and incrementally execute each migration step.

Each phase is based on the requirements and other outcomes of the previous one, allowing the verification of consistency of tasks performed and also the repetition of some activities in case the migration requirements are not fulfilled during the process execution.

Also, the process is structured in a top-down approach for the definition of migration steps, starting from the identification of business goals at company level and going down to the definition of a specific migration scenario and then deeper to the detailed technical solution to be implemented.

A key element of the present migration process is the investigation of alternative options. For each migration step different solution options are considered in detail and selected according to the evaluation of their impact at different dimensions of the factory. If all socio-technical impacts on the production system are included, the migration strategy is holistic.

The collection and selection of intermediate short-term goals enable an incremental procedure by implementing new components or changing part of the current system always in the direction of a higher digital maturity level of the production system. Therefore, agility is given by the possibility to change long- and short-term goals as required as well as to reversed decisions. The five phases, as structured, confer flexibility to the approach since they refer to one step at time and enable the backward iteration as soon as it is evident that the solution does not meet the requirements. Moreover, at each migration step, i.e. iteration of the entire process, the long-term vision and short-term goals are re-evaluated on the actual system conditions.

Besides the fulfilled requirements defined in Chapter 2.4, the value added of this approach is that it starts defining the migration strategy by considering the changed business paradigm rather than the technology transformation. Based on the business needs and the factory strengths and weaknesses, HoMoCPPS leads to the definition of a migration solution that is optimal for the manufacturers from a strategic point of view, and so brings economic benefit to the company.

The company should have first a clear picture of what should change in its business, and then the related technology implications can be derived. But technology is only one of the multiple aspects that need to be taken into account. By giving importance to the side effects of the technical implementation of the migration solution, such as operational and human impact aspects, HoMoCPPS aims at enabling the continuous business growth and effectiveness.

As described in Chapter 7, the discussed holistic migration approach has been implemented in different industrial environments in order to assess the validity of the approach. As a result of the industrial implementation, it can be concluded that the proposed HoMoCPPS approach is a novel, effective and systematic methodology for handling the migration towards cyber-physical production systems. The stepwise approach, the migration process and its methods and tools have been validated in the industrial environment. The industrial application of the approach proved that HoMoCPPS is a valid support for manufacturers to improve and evolve their production system according to new market requirements.

However, the limitation of the thesis lies on the methods related to the options investigation phase of the migration process. The identification and tradeoff of alternative migration scenarios represented in the migration matrix rely only on the knowledge and personal experience of the user. The solutions, and especially their impact at technical, operational and human dimensions of the factory, should be evaluated through a more standard approach that ensures the correctness of the tradeoff and can also speed up the evaluation process. A possible approach to control the migration process in a more standard way is the one proposed in [CaP18] with the use of Petri Net formalism.

Furthermore, the HoMoCPPS does not provide guidance on how to identify and collect all the possible migration options, especially in such evolving paradigm of Industry 4.0 in which the technology innovation is very rapid. The approach has been implemented only within research projects, focusing the range of possible migration option to the technologies available and proposed by the projects consortia.

Another limitation is the missing business dimension of the factory within the assessment questionnaire and the related low accurate KPIs evaluation during the design phase of the migration process. This is mainly due to confidentiality issues with manufacturers, who cannot share detailed information about their KPIs and economic calculations and make them available to the public.

In addition, the process could benefit from a more defined manner to select the appropriate implementation strategy after the migration solution is designed, i.e. big bang, parallel systems and phased introduction strategies, for the implementation and deployment phases.

Therefore, this work can be extended as following:

- Experience collected from other research projects that applied Industry 4.0 technologies in industry can be stored in a repository that, based on information about available technologies and their impact in production systems, can be used as a library of blueprints for migration steps to be reused in other migration projects;
- Following the same approach described above, migration scenarios could be automatically identified through a dedicated tool in which information gathered from technology experts and solution developers can be stored and correlated to other impact areas of a factory;
- To integrate the business dimensions in the evaluation of migration alternatives, quantitative indicators for evaluating benefits and associated KPIs should be provided, as well as business models supporting the required investments on Industry 4.0 technologies.

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Annex – Assessment Questionnaire

AT) Automation area – Technical dimension

AT01	**What is the Type of Automation System in Production?**
Level 1	The production is manual with the use of simple tools (not networked equipment).
Level 2	Production is performed by Automations (e.g. PLCs)
Level 3	The production facility has fully Automated Equipment (e.g. PLCs + SCADA)
Level 4	The production is Centrally Managed with support for operations like production scheduling etc. (It has MES and MOM).
Level 5	The Automation system can be automatically configured according to ERP product requirements.
AT02	**What is the Type of Equipment/Machinery in the shopfloor?**
Level 1	The equipment is Human Controlled (manual) with the use of special tools
Level 2	It is controlled by PLC automations
Level 3	It is controlled by PLC automation that belong in a local industrial network (networked)
Level 4	In addition to Level 3 (networked) the Equipment/Machinery provides an vendor specific API, that other systems could integrate with it
Level 5	The Equipment/Machinery is networked accessible with standardized mechanisms and exposes standard API (e.g. OPC-UA or MQTT)
AT03	**What are the CPS (Cyber-Physical-System) characteristics of the Product?**
Level 1	The product has no identification/serialization. This is the case in batch production
Level 2	The product has some kind of identification (e.g. Barcodes or RFID tags) that can be read from special equipment (e.g. barcode scanners, RFID readers) and transmitted through factory's network.
Level 3	Sensors and Actuators are attached on the product, that be used by production tools to interact with the product.
Level 4	Sensors and Actuators are attached on the product and sensor readings are processed by the product. Production logs and product's data can be read from the product electronically
Level 5	The product exhibits CPS functionality. It can respond to external requests and provide data or configured accordingly through the network.

AT04	**Do the devices have connectivity capabilities in the shop floor?**
Level 1	N.A
Level 2	A small part of the devices have basic connectivity (RS232 -RS485)
Level 3	Serial cable + LAN or WAN
Level 4	Most of them are with LAN or WAN and the other with serial cable
Level 5	All devices have full IP connectivity capabilities
AT05	**Do the devices in production stage deal with a security mechanism?**
Level 1	N.A
Level 3	basic security
Level 5	Full secured
AT06	**Do the devices in production stage deal with an access control mechanism?**
Level 1	N.A
Level 3	Local Access Control
Level 5	Global
AT07	**Is centralized control of physical Production processes available?**
Level 1	N.A
Level 2	The control exists in each production Station/equipment/machinery Control and central control is not offered.
Level 3	The production processes are controlled (start, stop, configured) from a centralized system (e.g. SCADA)
Level 4	The production (Control + Production Data) can be centralized managed from an IT system (MES+SCADA).
Level 5	The Production Processes are virtualized in the cloud. Multiple production facilities can be controlled and configured from the cloud.
AT08	**How machinery/equipment support Error Monitoring?**
Level 1	N.A
Level 3	Error monitoring is performed through external monitoring devices
Level 5	Each mancinery/equipment provides full error monitoring functionallity

AT09	**How the automation control system supports Error Monitoring of Production?**
Level 1	No monitoring is available
Level 2	It is performed per station/equipment/machinery.
Level 3	The monitoring is available through central supervisory system (SCADA).
Level 4	The monitoring is available through central supervisory system and the system provides error handling centrally (MES+SCADA).
Level 5	Errors are elevated to the cloud and Cloud Applications managing different production processes in different production facilities can respond accordingly (e.g. reschedule productions, if the error has large recovery time).
AT10	**How machinery/equipment support Performance Monitoring?**
Level 1	No Performance Monitoring
Level 3	Performance monitoring is performed through external monitoring devices
Level 5	Each machinery/equipment provides full Performance monitoring functionallity
AT11	**How the automation control system supports Performance Monitoring of the Production?**
Level 1	No Performance Monitoring
Level 2	Per Station / equipment. The equipment has its own performance UI.
Level 3	Performance data from different productions processes are collected and centrally (e.g. SCADA)
Level 4	Performance Data can be used for global production tracking
Level 5	On line Production Tracking in the cloud. ERP applications are able to have knowledge of the current production state.
AT12	**Are there specific protocols for the communication with the control devices?**
Level 1	NA
Level 2	RS485
Level 3	MODBUS
Level 4	PROFINET
Level 5	specific protocol unified for all (OPC-UA)

AT13	**Is there any access control service for any of automation Systems?**
Level 1	NA
Level 2	local
Level 3	There is different access control for each automation system (vendor based)
Level 5	Global
AT14	**Is there any secure mechanism for accessing automation fields or services?**
Level 1	NA
Level 2	basic security
Level 3	There is different secure mechanism for each automation system (vendor based)
Level 5	Full secured

AO) Automation area – Operational dimension

AO01	**How are equipment and production tool data managed?**
Level 1	The data are managed locally and it is are difficult to recover it
Level 2	The data are managed centrally, but still there are many local systems
Level 4	Most of the data is managed centrally, but still there are some local systems
Level 5	The data is managed centrally between industrial engineers, programmers and fixtures design of the equipment of production processes
AO02	**How is order processing executed within production process ?**
Level 1	The orders processing is neither automated nor integrated. It is labour-intensive.
Level 2	The orders processing is partially automated, but not integrated. Electronic worksheets are used but the process is characterized by high level of labour intensity
Level 3	The orders processing is automated, but not fully integrated. The integration with forecasting activities is manually realized
Level 4	The orders processing is automated and processes are being developed to be fully integrated.
Level 5	The processing of orders is fully automated and integrated.

AO03	**How is the Reconfiguration of shop floor equipment performed?**
Level 1	Manual by the operators.
Level 2	It is performed throw HMI localy in machine level
Level 3	It is performed throw HMI localy in machine level with predefined configuration sets
Level 4	It can be reconfigured from a central supervisor system (SCADA)
Level 5	Production Processes can be reconfigured according to the business requirements (ERP system).
AO04	**How is the Reconfiguration of the physical Production processes performed?**
Level 1	Manual by the operators.
Level 2	It is performed per Station/Equipment (in the PLC level) by configuring it.
Level 3	It can be reconfigured for the whole production facility from a central supervisor system (SCADA)
Level 4	Reconfiguration is centrally performed by an IT system (e.g. MES or MOM).
Level 5	Production Processes can be reconfigured according to the business requirements (ERP system).
AO05	**What is the Reconfiguration effect on production (e.g. on a Production line)?**
Level 1	Stops the production. Manual reconfigurations are needed that are time consuming.
Level 3	Stops the production, the configurations done per production stage using tools and software (e.g. flashing PLCs with the new production code etc.). Less time consuming than manual configurations but it also takes considerable time.
Level 5	Stops the production process shortly. Reconfiguration of all station is done centrally and automatically with centralized tools (e.g. SCADA) and protocols (e.g. IEC 61499). The whole production line is configured.
AO06	**How is the quality inspection performed in the shopfloor?**
Level 1	N.A
Level 2	The quality insepction is performed by operators
Level 3	There are automated quality inspection modules in critical points of production line
Level 5	There is a full automated quality inspection system which monitors every stage of the production

AO07	**Is the maintenance system installed in the shopfloor automated?**
Level 1	Every time an equipment is broken, it is manually repaired or replaced
Level 3	Based on historical data the operator schedules maintenance processes
Level 5	A centralized system schedules machinery maintenance and reconfiguration
AO08	**Are the information needed to draw up the master plan (sales forecast, inventory, etc.) made available and updated within the master plan?**
Level 1	Such information is not available or, if they are, are obsolete. Therefore, the Master Plan is not continually updated
Level 2	This information is available, but they are not updated in the Master Plan
Level 3	Such information is available and updated within the Master Plan
Level 5	This information is available in real time, so the Master Plan is dynamically updated
AO09	**How is the material planning process defined?**
Level 1	It is not defined.
Level 2	It is defined using a classic procedure of MRP (material requirements planning), taking into account infinite production; the procedure is executed but specific corrections to resulting plan order are not applied.
Level 3	It is defined using a classic procedure of MRP (material requirements planning), taking into account infinite production. The procedure is executed, and specific corrections to resulting plan order are applied, taking into account the internal constraints of production capacity and the eventual feedback of suppliers
Level 4	It is defined using a classic procedure of MRP (material requirements planning), considering constraints of internal production capacity the eventual feedback of suppliers.
Level 5	There is an integrated procedure which allows to obtain a feasible plan, taking into account the constraints of internal production capacity and feedback of suppliers; moreover, using a continuous updating of shop floor, capacity constraints are dynamically aligned with the current status of the production-logistic system
Management	**How Maintenance/Upgrading of the factory automation/IT solution influences the actual production?**
Level 1	The Automation Systems Architecture is centralized (monolithic). Changes to the system takes the automation system offline (stops the production) until the maintenance is completed. If the upgrade is not backwards compatible there

	should not be any production in the shopfloor during the upgrade process, thus the time to clear the production lines should be considered
Level 2	The System is Component /Modular based but centralized. Depending on the part of the system that is under maintenance, there could be partial downtime or full downtime until the processes are fully upgraded. For applications that involve on the actual production, if the upgrade is not backwards compatible there should not be any production in the shopfloor during the upgrade process.
Level 3	The System is Component Based and De-centralized. Each automation is process is self-contained. Production could be possible in the production stations that are not updated, especially if the upgrade is backwards compatible. If the upgrade is not backwards compatible there should not be any production in the shopfloor during the upgrade process.
Level 5	The System is Component Based and De-centralized and can run multiple instances/versions in parallel. This functionality is possible when the system follows Service Oriented Architecture principles and approaches1. The production is never going offline as each product is associated with a specific version of the production processes that will never go offline during its lifecycle, even when an component upgrade is taking place. The old component will continue to exist, serving the ongoing production process based on that component version. New products, once the upgrade has been finished will be able to use the newer version of the production process.

DT) Analytics area – Technical dimension

DT01	**Are there any collecting data devices (sensors sensor nodes etc) monitoring the shopfloor?**
Level 1	N.A
Level 2	Basic connectivity to some specific places (LAN)
Level 4	Connectivity infrastructure covers the most place of shop floor
Level 5	full connectivity (lan-wan- WSN - Lora)
DT02	**How the Data Processing of the Production is performed?**
Level 1	No Production Data are stored
Level 2	The Production data are stored locally in the local equipment. Manual extraction of these data is possible (through mass storage devices (usb disks) or even the network (ftp)).
Level 3	The Production Data are gathered to a central data repository (e.g.

	database or log).
Level 4	The Production Data from all stations are centrally stored, evaluated and analysed inside the factory (Factory Level).
Level 5	The Production Data from different production facilities are gathered, evaluated and analysed in a cloud platform (Cloud Level).
DT03	**Is there any pre-processing capability to the data collection phase?**
Level 1	N.A
Level 3	There is pre-processing capability to the field level
Level 5	There is pre-processing capability only to the factory level
DT04	**Is there specific API for analytic data/results, allowing other Systems connecting to it?**
Level 1	N.A
Level 3	Other systems can be connected with custom Interfaces
Level 5	Every Enterprise system can access analytics data through a well defined API
DT05	**Is there any quality and performance monitoring for the production lines?**
Level 1	N.A
Level 2	An elementary monitoring in local level using manual data
Level 3	A basic monitoring in local level using a restricted set of collected data
Level 4	There is a central factory system which monitors the quality and performance of the production line by collecting and analysing data from whole production line
Level 5	A cloud based infrastructure as Level 4
DT06	**Is there any system/process for preventive/predictive maintenance for the equipment /machinery in the production line?**
Level 1	N.A
Level 2	Manual process which defines human auditing activities
Level 3	Manual process which defines human auditing activities enhanced with some monitoring data
Level 4	There are collecting data which monitors the machinery/equipment operation during time and an automated process which predicts the life maintenance time

Level 5	A full automated process in cloud environment

DO) Analytics area – Operational dimension

DO01	**Are historical data coming from the quotation process recorded, stored and utilized?**
Level 1	No, there is no ability on detecting historical data and on utilizing them for the quotation of similar works.
Level 2	The ability to detect historical data is limited; for this reason, data are not systematically used for the quotation of similar works
Level 3	There is a good ability to detect historical data; nevertheless, data are not systematically used for the quotation of similar works.
Level 4	Historical data are systematically detected and used for the quotation of similar works
Level 5	Historical data are globally recognized, thanks to the availability of knowledge management tools; in addition, they are systematically used for the quotation of similar works.
DO02	**Which technology is utilized to support data acquisition (costs and other information) during the quotation process?**
Level 1	No technologies are used. The acquisition of data is performed by paper or by e-mail or fax
Level 2	The electronic sheets/ excel files are used for data collection, but the information is too scattered to be easily accessible
Level 3	Databases for data collecting are used, but they are not always easily accessible.
Level 4	The workflow is automated, then each data is plotted and stored and it is easily accessible
Level 5	The workflow is fully automated, so each data is plotted and stored and it is easily accessible; Furthermore, the automation of the workflow also allows to provide real-time data
DO03	**How do you manage the concept process during the product generation phase?**
Level 1	The process of concept generation starts from scratch for each new product. No data is collected from similar projects (new product development) to be reused
Level 2	The process of concept generation sporadically uses and reuses data collected from existing projects (new product development)
Level 3	The process of concept generation uses and reuses in a moderate way data collected of similar projects (new product development)

Level 4	The process of concept generation always uses and reuses collected data of similar and existing projects (new product development).
DO04	**How well is product data acquired and organized by engineers?**
Level 1	The engineers lose much of their time in searching for product data. Most of the time, these data are recreated, because they are not found or can not be acquired in that specific format.
Level 2	The engineers lose much time in searching for product data. Most of the time the data is re-created as it can not be acquired efficiently in that specific format
Level 4	The engineers lose little time in searching for product data. Nevertheless, most of the time, data is recreated. The data include mechanical, electrical and software information
Level 5	The engineers lose very little time in searching for product data and most of the time the data is re-used for new projects (new product development). The data include mechanical, electrical and software data
DO05	**How Bill Of Material (BoM) is managed?**
Level 1	The BOM is stored locally, in the form of electronic file/excel file. It is shared by e-mail, as there is not a repository of product data
Level 2	The BOM is managed in the form of electronic file/excel file but it is a shared in a common file through a sharing system and it is controlled by password
Level 3	The BOM is managed in a dedicated system. It is shared with other company functions, but this requires a lot of effort.
Level 4	The BOM is managed in a dedicated system. The loading of data is partially automated
Level 5	The BOM is managed in a dedicated system. Data loading is fully automated and it is synchronized in real time with the systems of other company functions.
DO06	**How does drawing management work?**
Level 1	The designs are managed in a paper form with supporting documentation.
Level 2	The drawings are managed electronically together with supporting documentation; they are printed before being approved
Level 4	The drawings are managed totally electronically, together with the supporting documentation and reference models, which, however, are not connected with components already realized
Level 5	The drawings are managed totally electronically, together with the supporting documentation and reference models, which are connected with components already realized.

DO07	**How are the short-term programs (i.e. the schedules) generated on the computer side?**
Level 1	The production schedules are received directly from the central office and the schedules of the material are derived locally. These are not made with integrated systems, such as MRP or ERP
Level 3	The production schedules are received directly from the central office and the schedules of the material are generated by MRP or ERP, but without considering any capacity limit and very often are not performed
Level 5	All short-term planning activities necessary to obtain feasible schedules, are performed by the MES type systems, which are integrated with ERP systems
DO08	**During the product requirements validation phase, do you consider the production performance, costs and delivery time?**
Level 1	No, requirements are not validated nor tracked
Level 2	No, requirements are not validated, but they are tracked in an unstructured way
Level 3	Yes, requirements are validated and tracked in a structured way, focusing especially on costs
Level 4	Yes, they are validated and tracked in a structured way. In addition the organization has the ability to predict a series of errors in order to avoid to re-design the whole process (and in order to avoid a cost hike)
Level 5	Yes, the organization has the ability to pre-validate the requirements, thus avoiding any kind of error that has impact on costs, delivery times and production performance
DO09	**How the internal requirements (defined by internal stakeholders) are compared with those initially defined by the customer?**
Level 1	The comparison is not carried out and the requirements are not verifiable. Not even during the latter stages of product development process. In fact, the product characteristics cannot be verified with those initially required by the customer
Level 2	The comparison is performed only during the latter stages of product development process, but it is done manually and it requires a long time
Level 4	The comparison is carried out quickly during the latter stages of product development process
Level 5	The product characteristics are constantly monitored during the development process; moreover, they are known by the whole company

	(including suppliers). The comparison between internal and external requirements is systematically performed.
DO10	**Are work-balance balancing studies conducted during the design of the production system?**
Level 1	No, the design choices are not based on workload; Hence, work is likely to be unbalanced
Level 2	Yes, the analysis of load balancing is performed by identifying in an approximate manner (i.e. mean value) the "bottleneck" of overall system
Level 3	Yes, the analysis of load balancing is carried out by identifying in an approximate manner (i.e. mean value) the bottleneck" of overall system; furthermore the sensitivity analysis is provided to understand the impact of different operating scenarios and related production targets (e.g. the level of the period's average demand)
Level 4	Yes, the analysis of load balancing is carried out by identifying more accurately, through dynamic/ stochastic models of production system (i.e. analytical or simulation), the bottleneck of overall system; furthermore the sensitivity analysis is provided to understand the impact of different operating scenarios and related production targets
Level 5	Yes, the analysis of load balancing is carried out by identifying more accurately, with dynamic / stochastic models of the production system (i.e. analytical or simulation), the bottleneck of the system; Sensitivity analysis are carried out to understand the impact of different operating scenarios and related production targets; it is also measured the uncertainty of achieving the objectives, considering the most impactful variability (e.g. faults, demand variability, ...)
DO11	**Is failure analysis carried out to identify root causes of production process (at the shop-floor level)?**
Level 1	No
Level 2	Yes, but the analysis is only occasionally performed. There is no standard procedures, and it is strongly dependent on the analyst experience.
Level 3	Yes, standard practices are defined for problem monitoring and for root causes identification
Level 4	Yes, standard practices are defined for the problems monitoring and the for root causes identification; the goal is to introduce mechanisms to prevent errors re-occurrence.

Level 5	Yes, standard practices are defined for problem monitoring and research of the root causes are followed in a systematic way; thanks to this practice, the organization has the ability to detect process variation or quality problems they occur; Furthermore, the effectiveness of the solutions adopted to reduce the problems is monitored ensuring the continuous improvement
DO12	**During the planning activity and the scheduling activity, do you verify the performance of production system affected by bottlenecks and material flow management?**
Level 1	There is no analytical approach to performance verification
Level 2	There are rudimentary tools - analysis of average values - for the performance verification; in particular, it proceeds to a comparison between available capacity and workload required for each planning period
Level 3	There are some advanced analytical tools - e.g. based on queuing theory - for the performance verification; in particular, there shall be an estimate of manufacturing performance including the crossing time
Level 4	There are analytical tools - e.g. based on queuing theory - for the performance verification; in particular, there shall be an estimate of manufacturing performance including the time of crossing; Moreover, the tools are integrated with accurate data relating to the constraints of the production system and layout of the production process plans
Level 5	Analytical tools - e.g. based on queuing theory - for verifying performance are enhanced with analysis by means of simulation models; in particular, there shall be an estimate of manufacturing performance including the time of crossing; Moreover, the tools are integrated with accurate data relating to the constraints of the production system and layout of the production process plans
DO13	**Do you carry out specific measurements in order to monitor the assets performance?**
Level 1	No, they are not carried out measurements. The productivity of assets fluctuates drastically, but there is no effort to manage the problem and try to put improvements
Level 2	Yes, measurements but only critical machines are monitored and controlled are carried out

Level 3	Yes, performance measurements of assets and are monitored and controlled are carried out
Level 4	Yes, measurements are performed and are put into practice metrics for the measurement and improvement of the various critical processes for the company's competitiveness
Level 5	Yes, measurements are performed and are checked frequently: continuously trying to improve and optimize these measures for better competitiveness
DO14	**How do you define the maintenance plans in your company? Is it dependent on quantitative analysis evaluation for estimating the best frequency in order to carry out the correct preventive maintenance activity?**
Level 1	There is no defined maintenance plan
Level 2	The maintenance plan is defined based on the experience of the operators responsible for the management / maintenance planning
Level 3	The maintenance plan is defined based on the experience of the operators responsible for the management / maintenance planning, and starting from the manufacturer's recommendations
Level 4	The maintenance plan is defined starting from the manufacturer recommendations and using quantitative analysis tools to define / redefine the best frequencies to make preventive maintenance
Level 5	The maintenance plan is defined by evaluating the results obtained with the existing plans and using quantitative analysis tools for (i) define / redefine the best frequencies to do preventive maintenance and (ii) to ensure the continuous improvement
DO15	**Do you perform failure analysis to identify critical machines / technical locations for the plant?**
Level 1	No
Level 2	Yes, even if the fault analysis is only occasionally developed without standard procedures. It is strongly dependent on the analyst experience
Level 3	Yes, standard practice for analysing failures are defined
Level 4	Yes, standard practice for analysing failures are defined, using techniques to search for the root causes of problems
Level 5	Yes, standard practices for fault analysis and research into the root causes

	are followed in a systematic way; Furthermore, the effectiveness of the solutions adopted to reduce the problems is monitored, ensuring the continuous improvement
DO16	**How do you carry out the data analysis of production inspections / monitoring and how do you take decisions about the maintenance condition?**
Level 1	No focused analysis using specialized software is carried out. no systematic data archiviation is carried out the decisions are mainly based on the information available in the latest inspection / testing
Level 2	Accurate analysis of the asset conditions using specialized software to support technical decisions are carried out.
Level 4	Accurate analysis of the asset conditions using specialized software to support technical decisions are carried out; data collecting within in CMMS and / or other specialized tools for maintenance is carried out in order to better define the frequency of the maintenance plan
Level 5	Accurate analysis of the asset conditions using specialized software to support technical decisions are carried out; data collecting within in CMMS and / or other specialized tools for maintenance is carried out in order (i) to better define the frequency of the maintenance plan and (ii) to support decisions about the scheduling of plant shutdowns based on the prediction of residual lifetime
DO17	**Is the Analysis of the production (Performance, Alarms, events) available with different granularity levels (e.g. Production Manager, Engineers, Operators)?**
Level 1	N.A
Level 2	Reporting is done by forms (filled by workers) and gathered for manual reporting. Large processing time (time-scale of days) of these reports
Level 3	Tools allow for gathering this data to a centralized system (MES). Data are exported for further analysis with the use of external analysis tools. Processing time large (time-scale of hours)
Level 4	Applications centrally process and analyse the production data. Processing time small (time-scale of minutes) but the analysis results are not fine-grained. Everyone has the same access level to these results.
Level 5	Applications process and analyse the production data. The applications provide different views of these data according to user roles. Processing time small (time-scale of minutes).

DO18	**Is there any data model used for analytics?**
Level 1	N.A
Level 3	Many different topic data models without a global data model
Level 5	A global data model
D019	**How the production optimization is performed?**
Level 1	N.A
Level 2	Manually by the operator
Level 3	Manually by the operator with limited support of local IT infrastructure
Level 4	The operator uses the results of a central system which analyse all possible suggestions of the production, and chooses the optimal solution in non real time
Level 5	The operator uses the results of a central system which analyse all possible suggestions of the production, and chooses the optimal solution in real time

ST) Simulation area – Technical dimension

ST01	**Does the company use specific tools for simulation during the concept validation phase?**
Level 1	We do not use simulation tools for the concept validation phase. Only the physical prototypes are extensively used.
Level 2	There are simulation tools, but physical prototypes are still extensively used
Level 3	The simulations are developed in CAD environment, which is used to create and validate the concept design; there is still a moderate use of physical prototypes
Level 4	The simulations are developed in CAD environment, which is used to create and validate the concept design. Only the interfaces between different components are examined using physical prototypes
Level 5	The simulations are developed in CAD environment, which is used to create and validate the concept design. The interfaces between different components are examined in the virtual way (in the same CAD environment)

ST02	**Are 3D layouts, visualization and simulation tools used for designing the layout and commissioning of the systems?**
Level 1	The layout is developed through CAD systems that are not dependent on on technical data related to products, production processes / material flows and equipment
Level 2	The layout is developed by CAD systems. The technical data relating to products, production processes / flows of materials and equipment are manually inserted.
Level 3	The layout is developed by CAD systems. These systems are interfaced with other design systems in order to have technical data on products, processes / flows of materials and equipment
Level 4	The layout is developed by CAD systems. These systems are interfaced with other design systems to have data related to production processes / materials flows and equipment. Some intelligent systems / algorithms are available for fast layout development
Level 5	The layout is developed through fully integrated CAD systems. These systems are fully interfaced with other design systems to have data related to production processes / flows of materials and equipment. Some intelligent systems / algorithms are available for the rapid layout development; Algorithms are used by the designer in a strongly integrated form with computer aided tool during his interactive design process.
ST03	**Is Optimizing Production using Simulation tools an option?**
Level 1	No such functionality available.
Level 3	It can be done offline. Requires data extraction and the use of a simulation platform.
Level 5	The automation system is optimizing its production by feeding a simulation service and getting back the simulation result that recommends the required decisions or the optimizations needed. The optimization could be automatic or a human can decide by viewing the simulation results.

SO) Simulation area – Operational dimension

SO01	**Are What-IF- Scenarios when changing Production (plan, mix, and physical configurations) supported?**
Level 1	No such functionality available

Level 3	Done by a production expert using external tool. It is not realtime and time consuming especially if it needs manual gathering of production data.
Level 5	The operator or the production manager is able to see a prediction on what the change of the production will case, taking into account the current and future state (products currently being produced in the shopfloor and products that are scheduled for production shortly). It could be a Cloud Service.
SO02	**Does the company uses simulation activity to test equipment, hardware, tools?**
Level 1	No, there is no simulation tests; furthermore it lacks the skills test performed by physical prototypes
Level 2	No, the simulation is not used, as the only tested tool is the physical prototypes
Level 3	Yes, the simulation is partly used, but a lot of time physical prototypes are utilized
Level 4	Yes, the simulation is used, in a balanced way with physical prototyping
Level 5	Yes, the simulation is strongly used, joined with physical prototypes utilization in order to finalize the test.
SO03	**How are production long term planning information supported (long-term)?**
Level 1	The information available for planning industrial assets is limited
Level 2	The information available for planning industrial assets is largely paper-based (eg technical archives); Access is therefore highly manual and takes a long time
Level 3	It is possible to access the information available for industrial assets planning, but these are accessible through dedicated workstations (for various limits, such as: local databases, organizational constraints of access constraints)
Level 4	You can access the information available for industrial asset planning and these are in centralized databases
Level 5	There is an integrated information system that allows access to real-time information so that planning decisions can be made with more than adequate support
SO04	**Are accurate models of production process made available on production facilities?**
Level 1	No, there are no models for the production process in machinery

Level 2	Yes, models are available for the production process, but the models are very simplified (implemented with the use of generalists tools of Excel type); their usability is limited to the experience of the analyst
Level 3	Yes, models are available for the production process (implemented with the use of more specialized instruments), limited to specific functions (e.g. The mechanical and structural simulation)
Level 4	Yes, models are available for the production process (implemented with the use of more specialized tools), defined with greater level of integration of business functions, including various simulations of various processes, in terms of chemical and physical aspect
Level 5	Yes, models are available for the production process (implemented with the use of more specialized tools), defined with greater level of integration of functions, including various simulations of various processes, in terms of chemical, physical, and automation aspect

H) Human dimension

H01	**To what extent does the top management support the transformation towards Industry 4.0?**
Level 1	Does not know Industry 4.0 concepts
Level 2	Does not recognize the value of Industry 4.0
Level 3	Recognized the financial benefits to be obtained with Industry 4.0
Level 4	Is developing plans to invest on Industry 4.0
Level 5	Widespread support for the Industry 4.0 across the wider business
H02	**How is your IT department organized?**
Level 1	Not available
Level 2	External service provider
Level 3	Internal for traditional IT systems
Level 4	Internal for specific digital systems
Level 5	Internal for all systems from Field to Cloud
H03	**To what extent are employees equipped with the relevant skills for Industry 4.0?**
Level 1	No experience with digital technologies

Level 2	Little experience with digital technologies
Level 3	Technology focused areas have employees with digital skills
Level 4	Most areas of the business have well developed digital and data analysis skills
Level 5	All across the business, cutting edge digital and analytical skills are prevalent
H04	**How the implications of digital technologies on Workplace and HMI adaptation have been addressed?**
Level 1	Still unclear
Level 2	Identified in general terms
Level 3	Analyzed
Level 4	Defined
Level 5	Implemented and incorporated in continuous improvement
H05	**How the implications of digital technologies on production roles and responsibilities have been addressed?**
Level 1	Still unclear
Level 2	Identified in general terms
Level 3	Analyzed
Level 4	Defined
Level 5	Implemented and incorporated in continuous improvement
H0X	**How the implications of digital technologies on X roles and responsibilities have been addressed?**
Level 1	Still unclear
Level 2	Identified in general terms
Level 3	Analyzed
Level 4	Defined
Level 5	Implemented and incorporated in continuous improvement