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Development of Industry 4.0 systems in SMEs environments

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Eines zu sein mit Allem, das ist Leben der Gottheit,
das ist der Himmel des Menschen.

Essere uno con il tutto, questo è il vivere degli dèi;
questo è il cielo per l'uomo.

Friedrich Hölderlin, Hyperion oder der Eremit in Griechenland
Traduzione di G. V. Amoretti

La logica vi porterà da A a B.
L'immaginazione vi porterà dappertutto.

Albert Einstein

Industry 4.0 does not require large sums of money.
Instead, application of proper concepts and existing fixed expenses
could be allocated for what fulfills Industry 4.0 specifications.

Chen, J. Y., Tai, K. C., and Chen, G. C. (2017).
Application of programmable logic controller to build-up an
intelligent industry 4.0 platform.
Procedia CIRP, 63, 150-155.

Abstract

Industry 4.0 is the current fourth industrial revolution, which is continuously modifying industrial environments towards technology evolution dealing with ongoing social, economic, and political changes. As a result, companies working in several industries are facing the need for disruptive industrial applications and their business evolution. Small and Medium Enterprises, that traditionally strive to keep up with industrial revolutions since they often are unprepared to understand novelties and to deal with changes that revolutions bring, often fail to identify how they must adapt to new industrial scenario. Dealing with this issue, especially the lack of knowledge of manufacturing Small and Medium Enterprises about new technologies and their gap in recognizing new business principles, this thesis proposes a two-fold approach. Firstly, the recent literature on Industry 4.0 in the engineering field is reviewed for identifying a simple technology stack of Industry 4.0, that can be easily understood also in environments that lack advanced knowledge of technology evolution. The technology stack is provided in the form of a Reference Model, since its suitability for identifying components needed for coping with industrial changes. The model is tested verifying its interoperability with other relevant Reference Models and Architectures of Industry 4.0. Secondly, a Maturity Model is designed, capable of assessing whether manufacturing companies have adopted recent disruptive technologies of Industry 4.0 and they comply with its new business principles, and in which direction they must evolve considering the supply chain in which they do business. The Maturity Model is then tested in the manufacturing and processing agro-food industry of the food valley, located in the Parma district of the Emilia-Romagna region, in Italy.

L'Industria 4.0 identifica l'attuale quarta rivoluzione industriale, in cui la continua evoluzione delle tecnologie permette di rispondere con successo ai continui cambiamenti sociali, economici e politici. Di conseguenza, le aziende, a prescindere dal settore in cui operano, affrontano la necessità di realizzare applicazioni industriali totalmente nuove e far evolvere il proprio modo di fare business. Le piccole e medie imprese, che tradizionalmente soffrono le rivoluzioni industriali poiché spesso sono impreparate a comprenderne le novità e ad affrontare i cambiamenti che ne derivano, spesso non riescono a conformarsi al nuovo scenario industriale. Per affrontare questo tema, e in particolare la mancanza di conoscenza delle nuove tecnologie da parte delle Piccole e Medie Imprese del settore manufatturiero, e la loro incapacità di riconoscere nuovi principi di business, questo lavoro di tesi propone un duplice approccio. In primo luogo, la recente letteratura sull'Industria 4.0 nel campo dell'ingegneria viene rivista per identificare un semplice stack tecnologico dell'Industria 4.0, che possa essere facilmente compreso anche in ambienti che non hanno una conoscenza avanzata delle recenti evoluzioni tecnologiche. Lo stack tecnologico viene proposto nella forma di Reference Model dell'Industria 4.0, in quanto questa tipologia di modello è adatto a identificare i componenti necessari per affrontare i cambiamenti industriali. Il modello viene testato verificandone l'interoperabilità con altri rilevanti modelli e architetture di riferimento dell'Industria 4.0. In secondo luogo, viene progettato un Modello di Maturità in grado di valutare se le aziende manifatturiere hanno adottato le nuove tecnologie dell’Industria 4.0 e si sono adeguate ai nuovi principi di business, e in quale direzione devono evolvere considerando la supply chain in cui operano. Il Modello di Maturità viene poi testato in un ambiente specifico, cioè l'industria agroalimentare manifatturiera e di processo della food valley situata nella provincia parmense in Emilia-Romagna (Italia).

Acknowledgements

This thesis is the result of a three-year journey. Of course, it has been possible thanks to the support of my professors and colleagues. First, I want to thank prof. Eng. Massimo Bertolini, who have thought the research carried out in this opera. Second, prof. Eng. Giovanni Romagnoli deserves a special mention. From the very start, he taught me how to research, and he has been a constant reference all along the way. Moreover, I want to thank prof. Dr-Eng. Dieter Uckelmann, whose suggestions have contributed to my career development (I hope) and my personal growth (I am sure of this). Then, I thank other people who have been stimulus and sources of inspiration: prof. Eng. Antonio Rizzi, prof. Eng. Francesco Zammori, and my Ph.D. colleagues Dr-Eng. Davide Mezzogori and Dr-Eng. Mattia Neroni. Furthermore, I want to thank other collaborators who have accompanied me along the journey, in particular Roberto Buratti from SMILE DIH.

Additionally, I offer my regards and blessing to all my family and my friends, who have also contributed to my serenity and have been supportive in good and bad times. Especially, I want to thank my father, to whom I owe to be an engineer. And I send a thought to my deceased mother, who I am sure has assisted me from afar in this journey. I further thank my siblings and relatives, and my friends: those who have always been there, and those I found again after a long time. If you have a copy of this thesis, you know that you are among the people I am thanking.

Finally, I dedicate this thesis to Graziana. She who has been able, as always, to bring out the best of me, even in the worst moments.

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Abbreviations used in this dissertation

The following abbreviations are used in this dissertation. Some are not properly acronyms, e.g. AS-IS, and they are used to simplify the reading. The declination of the acronym is valid, namely acronyms follow rules of using the plural in English. The language used in this thesis is American English.

3PM	*Third Part Manufacturers*
AS-IS	*Present-State*
ATO	*Assembly-to-Order*
B2B	*Business to Business strategy*
BD	*Big Data*
BDA	*Big Data Analytics*
BI	*Business Intelligence*
BM	*Business Model*
CPPS	*Cyber Physical Production System*
CPS	*Cyber Physical System*
DIKW	*Data-Information-Knowledge-Wisdom*
DMI4.0	*Digital Maturity Index for I4.0*
DT	*Digital Twin*
ER	*Emilia-Romagna (region in Italy)*
ERP	*Enterprise Resource Planning*
ETO	*Engineer-to-Order*
H2M	*Human to Machine communication*
HMI	*Human Machine Integration, i.e. Human-Computer and Human-Machine interactions*
I4.0	*Industry 4.0 (intended as a complex of principles and technology stack modifying industry and way of doing business)*
ICT	*Information and Communication Technology*
IDS	*Industrial Data Space*
IIoT	*Industrial Internet of Things*
IIRA	*Industrial Internet Reference Architecture*
IME	*Industrial and Manufacturing Engineering*
IMS	*Intelligent Manufacturing Systems*
IoS	*Internet of Service*
IoT	*Internet of Things*

IT	*Information Technology*
LE	*Large Enterprise*
M2H	*Machine to Human*
M2M	*Machine-to-Machine communication*
MES	*Manufacturing Execution System*
MM	*Maturity Model*
MTO	*Make-to-Order*
MTS	*Make-to-Stock*
OM	*Operations Management*
OT	*Operational Technology*
PPC	*Production Planning and Control*
RA	*Reference Architecture*
RAM	*Reference Architecture Model*
RAMI 4.0	*Reference Architecture Model Industry 4.0*
RFID	*Radio Frequency IDentification*
RM	*Reference Model*
RMI4.0	*Reference Model for Industry 4.0*
SC	*Supply Chain*
SCM	*Supply Chain Management*
SF	*Smart Factory*
SM	*Smart Machine*
SME	*Small and Medium Enterprise*
SMfg	*Smart Manufacturing*
SP	*Smart Product*
SWOT4i	*SWOT Analysis for I4.0*
TO-BE	*Future-State*
VN	*Value Network*
XaaS	*'Something'-as-as-Service*
XTO	*Production strategies which differ from MTS, i.e. ATO, MTO and ETO*

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1 Introduction to the research

In 2013 the German government announced the 'Industrie 4.0' initiative with the aim of guiding the industries towards a revolution of the manufacturing sector (L. Da Xu, Xu, & Li, 2018). First introduced to a wide audience by the working group 'Zukunftsprojekt Industrie 4.0' at the Hannover Fair in 2011 (Jazdi, 2014), it has been followed by lots of similar programs, planned to align national-and-international strategic industry initiatives to new requirements of both market and society: for instance, the Chinese ten-year national plan 'Made in China 2025' (L. Li, 2018), USA national program 'Advanced Manufacturing Partnership' also known as 'Advanced Manufacturing 2.0' (Trotta & Garengo, 2018), and 'Factories of the Future' within the program 'Horizon2020' of the European Commission (Jardim-Goncalves, Romero, & Grilo, 2017). The term Industry 4.0 (I4.0) has been hence adopted worldwide for identifying this expected industrial revolution (Lasi, Fettke, Kemper, Feld, & Hoffmann, 2014; Yang Lu, 2017). In fact, although the individual changes in the manufacturing sector can be interpreted as an evolution of the third industrial revolution, there is a consensus that the speed and impact of these developments lead to the fourth industrial revolution (Schwaab, 2015). Several authors analyzed the evolution of manufacturing from different point of views. For instance, Xu et al. (2018) analyzed the industry journey from the technology perspective, while Yin, Stecke, and Li (2018) focused on the development and settlement of the production systems to respond to changing market demand. Whatever the perspective, it is possible to identify specific enablers to the initial three milestones (Lukač, 2015):

- The first industrial revolution was triggered by the introduction of mechanical manufacturing systems utilizing water and steam power.
- The second industrial revolution witnessed the introduction of mass production utilizing electrical power.
- The third industrial revolution involved the use of electronics and Information and Communication Technology (ICT) systems for the automation.

The fourth industrial revolution is the result of continuously pushing on digitalization and networking of industrial systems, towards a new intelligent stage of informatization (J. Zhou et al., 2018). I4.0 can be defined as the use of (i) integrated physical machinery and devices, and (ii) networked sensors and software[1]. This leads to new paradigms in terms of value chain organization and business models (BMs), as well as transformation of work organization and production technologies (Hermann, Pentek, & Otto, 2016; Kagermann, Helbig, Hellinger, & Wahlster, 2013).

Thus, I4.0 entails the deployments and optimization of very innovative technologies as well as detailed control of processes and business performances, and generally relates to aspects of supply chain (SC) complexity (Arnold, Kiel, & Voigt, 2016; Radziwon, Bilberg, Bogers, & Madsen, 2014). As a result, industry players are inclined to behave as if I4.0 is useful for mainly coping with concerns of large

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[1] Source: A global industry first: Industrial Internet Consortium and Plattform Industrie 4.0 to host joint IIOT security demonstration at Hannover messe 2017. Available from: https://www.iiconsortium.org/press-room/04-20-17.htm. Last access: 2020.10.14

enterprise (LE) managements, whereas I4.0 is just as important to small and medium enterprises (SMEs) than their top management and bottom staff are ready to recognize (Müller, Buliga, & Voigt, 2018).

1.1 Motivation behind the research

The importance of filling the gap in the SMEs readiness to I4.0 relates to the fact that the inability of SMEs to evolve in the new technology and business scenario can compromise the same businesses of SMEs eventually leading to their demise (Hopkinson, Hague, & Dickens, 2006), to the extent that *"the smaller SMEs are, the higher the risk that they will become victims instead of beneficiaries of the fourth industrial revolution"* since they are further less capable of coping with technology and staffing challenges than LEs (Sommer, 2015). On the other hand, the importance of the SMEs is arguable by considerations on what is the impact of SMEs on international economy. In the present thesis two of the main European economies are considered, namely the German and the Italian ones. Germany, as previously introduced, is the country that first comprehensively promoted I4.0, paving the road for the development of its principles and technologies. Italy, and especially the region Emilia-Romagna (ER), one of the most important to the country in terms of both economy and society[2], is the region in which this study has been carried out, and where it is directed to.

In Europe, SMEs are defined as firms employing fewer than 250 persons and having a total turnover that does not exceed EUR 50 million[3]. The relevance of SMEs in the European landscape is arguable by means of position of SMEs within the national economic contexts. This importance is here analyzed for German and Italian economies through information elaborated by the Statistisches Bundesamt (2017)[4] for Germany and from the European Commission (2018)[5] for Italy. Even if information is not consistent with years, it is however useful to the picture of European economic outlook justifying this study. The analysis is three-fold focused and it finds out: (i) the SMEs presence on national territories, (ii) their impact on the national total turnover, and (iii) the number of people employed. Table 1.1 reports data of two countries analyzed. Two economies clearly depend more on SMEs than on LEs.

Table 1.1 - The impact of SMEs on national economies as in Statistisches Bundesamt (2017)[4] and in European Commission (2018)[5]. Data in brackets refers to micro-enterprises, i.e. less than 10 employees as in European Commission (2008)[2]

Index	**Germany**	**Italy**
% of companies	99.3% (81%)	99.9% (94%)
% of total turnover	84%	67%
% of total nr. of employees	61%	80%

Concerning the main recipient of this study, the research focal area is the ER, a central-northern region in Italy. The study was a joint effort between ER industries and the University of Parma in the same region. Furthermore, ER has an important role in the economy of the country: out of 1,500,000 enterprises with at least one employee on the national territory, almost 120,000 are located in ER, only coming after two other regions, i.e. Lombardy (ca. 265,000 enterprises), and Lazio (ca. 150,000

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[2] Source: https://www.agi.it/fact-checking/dati_emilia_romagna_occupazione-6916680/news/2020-01-21/. Last access: 2020.06.25.

[3] Source; European Commission. 2008. "Un Small Business Act pour l'Europe [A Small Business Act for Europe]." Business, COM(2008) 394 final, 25. Retrieved from: http://www.eurosfaire.prd.fr/7pc/bibliotheque/consulter.php?id=2321. Last access: 2019.12.19.

[4] Source: https://www.destatis.de/DE/Themen/Branchen-Unternehmen/Unternehmen/Kleine-Unternehmen-Mittlere-Unternehmen/_inhalt.html. Last access: 2019.12.20.

[5] Source: file:///C:/Users/gioes/Downloads/Italy%20-%202018%20SBA%20Fact%20Sheet.pdf. Last access: 2019.12.20.

enterprises). This is more relevant by considering that Lombardy is the region of the country's economic capital[6] (i.e. Milan), and Lazio is the region of its geographical capital (i.e. Rome). Out of these 120,000 ER enterprises, 99.6% are SMEs.

Although it is clear the importance of SMEs companies in all countries' economies, they suffer from lack of adequate models and cultural deficits in dealing with novelties, because of their main characteristics (Mintzberg, 1982; Torrès, 1999):

- The organizational structure of SMEs is characterized by proximity management, which results in strong involvement of managers in all the company's decisions. In addition, SMEs lack experts supporting the own operations and functions, such as a SC, information technology, as well as financial managers.
- Most SMEs very often prefer short-term rather than long-term strategies, and this aspect can prevent significant long-term investments.

More in detail, gap in ordinary business relates to traditional SME lateness (Land & Gaalman, 2009): (i) inadequate capacity planning overviews to support sales decisions, (ii) uncontrolled delays in engineering and (iii) the inability to recognize general system readiness and specific order delays, and finally (iv) inability to amend uncorrected decisions. Whereas, a major issue in industry evolution is the lack within most SMEs of novelty-focused structure involved first in the acquisition of knowledge, and later in the development of solutions (Nowotarski & Paslawski, 2017). This generally leads to a further distance among small companies not receptive to industrial evolutions and few virtuous companies which are able to face the ultimate consequences of the industrial novelties, i.e. medium enterprise, of very specific sector or dependent on multinational companies (Raymond & Croteau, 2006).

1.2 Are SMEs ready for I4.0? An analysis of the AS-IS scenario

The inability of SMEs of grasping novelties, and their technology and management un-preparedness need to be further explored towards I4.0. In the European Union (EU) approach[7], a budget of €9,2 billion have been established to facilitate the transition of SMEs to the Industry 4.0 paradigm, focusing on systems integration and the ability to have and access data. The basic concept in which lies the European governments' approach is hence the industrial digitalization (Schumacher & Sihn, 2020). This industrial digitalization has led to an increasing availability of production and supply chain data as well as to the automation of formerly manual processes, along with development of society and economy, and positive effects on company performances (BarNir, Gallaugher, & Auger, 2003; D. S. Johnson & Bharadwaj, 2005; Kłos & Patals-Maliszewska, 2013; Zawadzki & Żywicki, 2016). Concepts such as cyber-physical systems (CPS) (Jazdi, 2014), and Internet of Things (IoT) (Uckelmann, Harrison, & Michahelles, 2011b) are supporting enablers to the diffusion of digital technologies and their integration into the production chain, with the aim of extending automation and data exchange in manufacturing. Hermann et al. (2016) have provided a review of academic and business works on I4.0, by means of which they have identified four I4.0 key components: beyond already cited (i) CPS, and (ii) IoT, (iii) smart factories (SF), and the (iv) Internet of Services (IoS) have been discussed. CPS is comprised of the networked infrastructure of interconnected physical components and a cyber network of intelligent controllers and the communication links among them (Parvin, Hussain, Hussain, Thein, & Park, 2013). IoT can be viewed

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[6] Source: https://www.prologis.it/industrial-logistics-warehouse-space/europa/italia/milano-capitale-industriale-e-finanziaria. Last access: 2019.12.19.

[7] Source: https://www.agendadigitale.eu/industry-4-0/industria-4-0-e-tempo-di-agire-il-piano-ue-a-sostegno-delle-pmi/. Last access: 2020.30.01.

as all physical things that can work as the so-called 'smart things' by featuring (small) devices that are connected to the internet (Fleisch, 2010). IoS is the idea that services are made easily available through web technologies, creating new kind of value-added services (Wahlster, Grallert, Wess, Friedrich, & Widenka, 2014). Services are commercial transactions in which those who provide the object of the transaction can temporary access the resources owning the same object, in order to perform a prescribed function and related benefits (Barros & Oberle, 2012). SF lies on the concept of the strong linkage and communication, over the IoT and the IoS, of products, machinery, transport systems, and humans in form of CPSs, enabling a decentralization of the production system (Kagermann et al., 2013). Moreover, three features of I4.0 have been identified by Kagermann et al. (2013), namely (i) horizontal integration, (ii) vertical integration, and (iii) end-to-end engineering integration. The horizontal integration allows to manage inter-collaboration through value networks (VNs). The vertical integration allows to manage production processes transparently and so they are reconfigurable through manufacturing networks. The end-to-end engineering integration allows to decentralize intelligences and to optimize processes through the convergence of the sub-system outputs within the factory and across the entire value chain (S. Wang, Wan, Li, & Zhang, 2016).

The benefits of this revolutionized industrial environment, among others, are the possibility of pursuing a highly flexible mass production system, the real-time coordination and optimization of value chains, the reduction of complexity costs, and the emergence of entirely new services and BMs (Hofmann & Rüsch, 2017). BMs can be defined according to Teece (2010) as the way *"a firm delivers value to customers and converts payment into profits"*. Hence, BMs represent the framework that allows to redesign the own way of doing things pursuing a better way than the existing alternatives (Magretta, 2002). In this sense, the way BMs have evolved is used in this thesis to expresses the way business has evolved over last decades, and thus to characterize the principles to which refer for investigating the SMEs gap in evolving towards the I4.0.

Prause (2015) clearly identifies three directions to which traditional businesses have to move for developing into BMs of I4.0. These three orientations are (i) open innovation, (ii) service design, and (iii) network approaches for manufacturing systems. In the following, an overview of these three concepts is provided, focusing on how results from relevant literature on SMEs.

Open Innovation

Open Innovation lies on the concept of going beyond corporate boundaries and sharing knowledge among sources to accelerate internal innovation process and to better benefit from innovative efforts (Henry William Chesbrough, 2003). The related concept of technology exploitation and technology exploration leverage on these inflows and outflows of ideas and knowledge (Lichtenthaler, 2008). Technology exploitation is the mechanism by which companies exploit their knowledge to get the most from business partners' technologies and processes. Whereas, technology exploration is the mechanism by which companies acquire knowledge from business partners for getting the most from technologies they own (Van de Vrande, De Jong, Vanhaverbeke, & De Rochemont, 2009).

Open Innovation has generally been neglected by SMEs, while its practices are widely accepted by LEs Actually, the study of Van de Vrande et al. (2009) has proved that European SMEs have shown interest and some progress towards the technology exploitation, whereas they do not delve into the technology exploration and for this reason this mechanism is not fully adopted. It is likely that this lack of balance for SMEs in fitting in with the two mechanisms comes from the real patronage nature of SMEs: they are willing to share their knowledge and technologies with business partners for acquiring market share, whereas, for instance, they are not able to force their business partners to acquire skills. The truth of this statement can lie on the evidence that the larger the SME is, the more it develops these strategies, to the extent that SMEs adopt these mechanisms most and widely (Lichtenthaler, 2008).

Service Design

Service design is the recent approach in industry for which the customer does not primarily purchase a product, rather he buys the service that the product or devices provide, with the consequence that the centrality of the product and the care of its design move to the service and its design (Stickdorn, Schneider, Andrews, & Lawrence, 2011).

It is proven that SMEs need to fill the gap in service design practices, especially they still miss to define consistent and efficient industrial configurations for their business process towards the service design, to an extent that seems that the smaller is the enterprise, more it does not dare to increase the value of the services provided (McDermott & Prajogo, 2012).

Networked Manufacturing Systems

Networked Manufacturing Systems push on the concept of interactions among business partners, aiming to a manufacturing system in which decision-making processes are distributed over the factory on the basis of events within the supply chain (Frazzon, Agostino, Broda, & Freitag, 2020). Manufacturing Network Systems are advanced manufacturing systems that leverage an intensive digitalization of processes to create geographically distributed manufacturing networks, pursuing a more efficient use of resources and a better control of production processes, together with reduction of costs due to production, storage and transportation processes, regardless the demand variability (Rauch, Unterhofer, & Dallasega, 2018).

These manufacturing systems are definitively adopted by SMEs. However, Raymond and Croteau (2006) have deeply analyzed the way SMEs do it, and consequences for their business. In their work, these authors state that although SMEs are able to work with their partners in the supply network, just companies that fully adopt advanced manufacturing systems are successful in doing their business. For instance, authors mention some tools adopted by SMEs supporting the networking, and they state that while ERP and CAD software are largely used, just few companies have recently adopted MRP techniques, and seldom they use EDI systems. With respect to the benefits of the networking, according to (Cagliano, Blackmon, & Voss, 2001) authors identify three alignment patterns. Firstly, local SMEs that develop their business focusing on market penetration through limited networks. Next, world-class SMEs develop themselves through diversification and networks. In the middle of these two alignments, there are the transition SMEs. The usefulness of switching from a local mindset to world-class practices and performances lies on the fact that world-class SMEs manage their manufacturing resources within the network to achieve better performances than transition SMEs and especially outdoing local firms.

1.3 Research questions of this thesis

As it emerges from the analysis conducted above, SMEs are not prepared to develop into I4.0 systems basically because they have not grasped yet the meaning of the recent evolution of industry and business which is the genesis of same I4.0. The main reasons are a cultural gap that still exist in small environment, the lack of specific knowledge about new industry rules, and, especially for the manufacturing sector, the unavailability of enabling technologies to face new functions of the production (Moeuf, Pellerin, Lamouri, Tamayo-Giraldo, & Barbaray, 2018). Furthermore, SMEs have a main concern to embrace specific I4.0 technologies since they have to face limited financial availability, which is a real constraint on closer alignment to redefinition of the own business and paradigms coming from an industrial revolution

(Huang, Lai, Lin, & Chen, 2013). These results are generally valid for the western SMEs, and especially for SMEs in ER region, where the rather patronage reality of companies from several areas makes the above-mentioned shortcomings typical.

The industrial environment of ER is mainly composed of SMEs[8] of the manufacturing and processing industry. This industry produces end products, (often) through a wide range of operations, from intermediate products provided by the basic industry (De Toni & Panizzolo, 2018). By long-term technology-transfer partnership between the University of Parma and the regional companies, it is possible to state that with respect to the Emilia district of the region, in which Parma is located:

- Different industrial sectors operate in the region, the most important relates to (i) textile industry, mainly in the Modena district as well as (ii) automotive industry, although SMEs of this sector are mainly subsidiary industries of (iii) heavy and mechanical engineering industry, widespread in all the ER region regardless the nature of downstream industries; (iv) secondary chemical (e.g. cosmetics, pharmaceutical) and biomedical industries, mainly based in Parma and Modena districts; and (iv) food & beverage industry, widespread in the ER although is widely recognized that Parma leads the industry[9]. Bologna deserves a special mention, since its manufacturing industry in general operates in a wide variety of sectors[10].
- The majority operates through process-oriented structures, characterized by (i) high flexibility, and (ii) complex SC networks. Manufacturing companies have paid attention to business solutions that improve both organization and operation management to respond to need of flexibility and to cope with SC complexity (Bertolini, Romagnoli, & Zammori, 2017). However, it is well-established that these companies are traditionally not able to face problems related to day-to-day management of business, and the industry evolution, because they have few knowledge of technologies, and process business management principles (Bertolini, Carmignani, & Zammori, 2009).

The present research project is mainly tailored to implementation of I4.0 technologies and principles within the SMEs in ER and surrounding areas, and especially the Parma district where the University of Parma is sited and where the university acts. The goal is to define a real "simplified development formula" of I4.0 systems, with the aim of (i) adapting their technologies and knowledge for the international state-of-the-art, and (ii) responding properly to changing industry and market requirements.

The research hence aims to answer to two main research questions (RQs). First RQ is the following:

(RQ1) How can reference models or reference architectures be adapted to promote adoption of I4.0 principles and technologies in SMEs?

This thesis addresses this question in chapters 2 and 3, where outcome (i.e. O1) outcomes are provided:

(O1) A reference model, that copes with the need of SMEs for intelligibility of novelties introduced by I4.0, is designed.

The second RQ is the following:

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[8] Source: Banca d'Italia. Economie regionali. L'economia dell'Emilia Romagna (2017). Gathered from link: https://www.bancaditalia.it/pubblicazioni/economie-regionali/2018/2018-0008/1808-emilia-romagna.pdf. Last access: 2019.12.31.

[9] Source: Ansa. Visit: https://www.ansa.it/emiliaromagna/notizie/speciali/2017/10/10/parma-cuore-della-food-valley-dellemilia-romagna_4de34e52-8a55-47aa-9891-da595c159f12.html. Last access: 2020.09.03

[10] Source: https://www.storiaememoriadibologna.it/il-modello-industriale-bolognese-una-metamorfosi-d-1312-evento. Last access: 2020.10.06

(RQ2) Does a maturity model exist that simply shine a light on principles and technologies to develop I4.0 systems within SMEs environment? Question is formulated regardless of the specificity of their location and of sector they operate in.

This thesis addresses this question in Chapter 4 where a second outcome (i.e. O2) is provided:

(O2) Then, a maturity model in Chapter 4 is designed, for assessing the maturity level of SMEs towards I4.0 system development and implementation.

Dealing with the maturity model design introduces a further research question:

(RQ3) Is the maturity model introduced in O2 effective and viable?

(O3) For answering this question, some use cases of O2 are provided. They relate to a study of the I4.0 maturity of the agro-food industry of the Parma district in the ER region.

Reference model and maturity model are selected because of the following reasons.

A reference model for a specific problem domain consists of as few unifying concepts and principles arranged a suitable abstract framework and it is independent of specific reality and its actual details in which it is used (MacKenzie et al., 2006). The reference model is hence used to simplify the basics of I4.0 to increase acceptance of these for SMEs, especially simple realities, sometimes totally virgin in recent industry evolution.

Maturity model is used since it provides many advantages in the adoption of particularly complex systems (Batenburg, Helms, & Versendaal, 2006; Neff et al., 2014; Savino, Mazza, & Ouzrout, 2012; Sharma, 2005; Wendler, 2012). Firstly, they allow to define longer-term roadmaps for investment decisions, as well as for identifying required novel competencies to develop. Secondly, they provide structured checklists for implementing the identified competencies. Thirdly, they allow the adoption process, usually complex, to be faster and more efficient. Fourthly, they depict the current AS-IS situation of a system in terms of several critical management areas. Fifthly, they successfully define the TO-BE systems with respect to desired future outcome.

A comprehensive literature review of both reference and maturity models in I4.0 is provided in the literature review section of the corresponding chapters devoted to the description of the outcomes of this thesis.

1.4 Methodology

First, a preliminary narrative literature review of I4.0, by means of ‘literature classics’, is carried out for identifying basic principles and components of I4.0. The term ‘literature classics’ is adopted in this thesis for referring to studies carried out in the early stages of academic and non-academic research and based on citation counts. A rigorous ‘disciplinary’ has not been adopted since it is not the scope of the review of judging research values. However, works published up to 2017 and counting more than 100 citations on scholar are here considered ‘literature classics’. Scholar is used since collects use of research in both academia and practitioner worlds. Moreover, this literature review of studies on I4.0 is used for fixing the vocabulary adopted in this thesis, namely I4.0 terms relevant to the study carried out in this thesis are fixed and their meanings provided.

Next, a waterfall approach is adopted in order to model O1 (i.e. a reference model) and O2 (a maturity model, that cope with research questions RQ1 and RQ2 respectively. The waterfall approach for modelling each outcome rearranges the ‘value ideation’ of the sustainable business model innovation of

Geissdoerfer, Bocken, and Hultink (2016), into the 'model ideation'. The general framework is provided in Figure 1.1. The framework identifies (i) three 'jumps' of the waterfall, i.e. Model Mapping, Model Prototyping, and Documentation, and (ii) several 'steps' for each jump. In the following, the methodology adopted is generally described, then the specific methods and tools used are provided for carrying out each stage of the research.

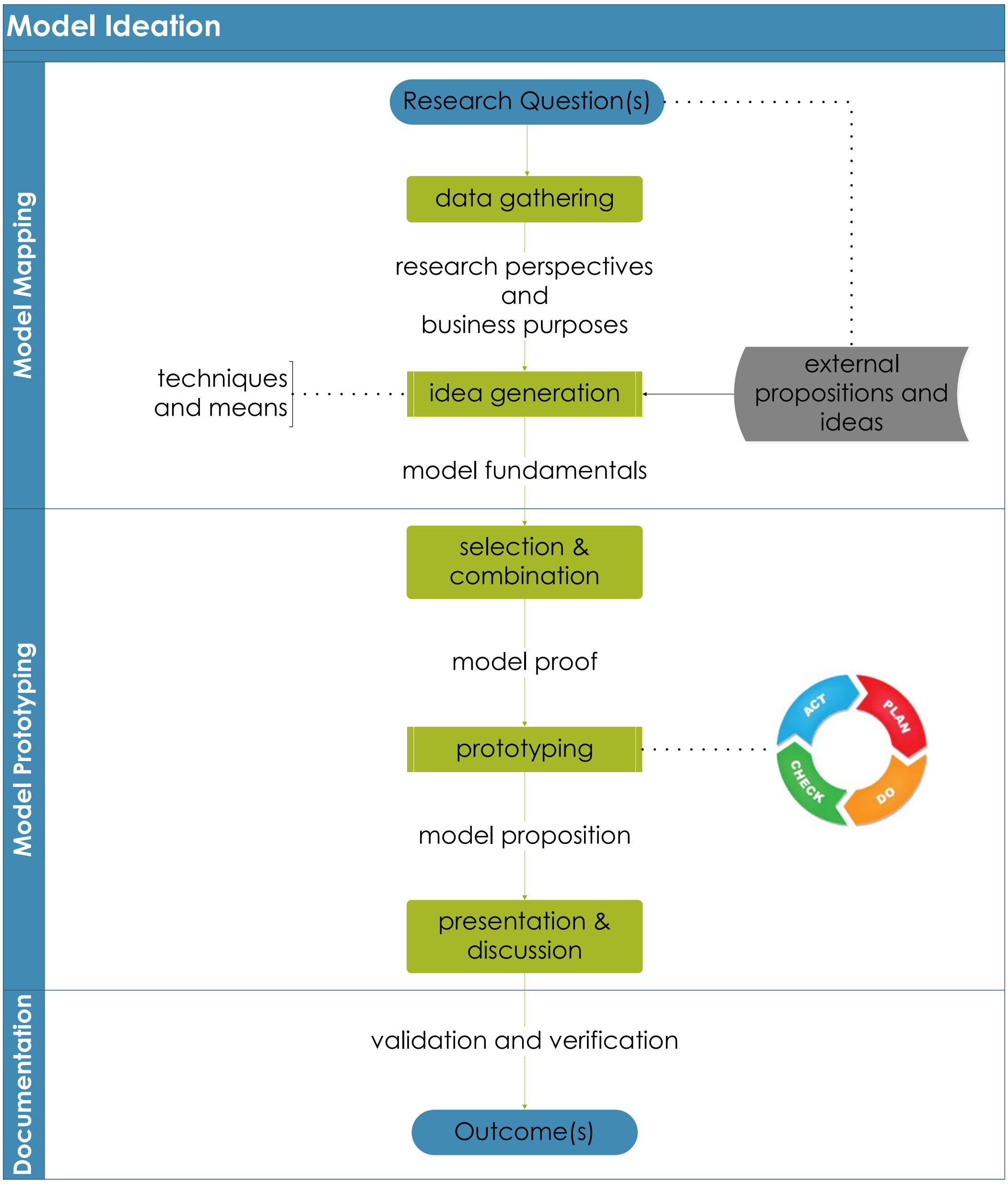

Figure 1.1. Framework for designing I4.0 models, rearranging Geissdoerfer, Bocken, and Hultink (2016)

The first jump entails preliminary designing a draft of the model. Once that the research is justified and the research questions are defined, data and information about the gaps in literature and the real business priorities are collected to generate ideas that develops into a sketch of the model, supported by experts' interviews where appropriate. This step is a real subprocess since beyond involving external interventions (if needed), it entails selecting the techniques and methods for designing the model. This aspect is emphasized in Figure 1.1 by means of a framed box, whereas blunt box identifies activities or processes. Once that the fundamentals of the model are identified, next jump first involves selecting and matching ideas and methods, for designing an early blueprint of the model, then its prototyping follows. This is a cycling subprocess, in which the classic Plan-Do-Check-Act[11] approach is adopted. This jump eventually ends with the validation and verification[12] of the model joining with stakeholders in discussing it. Last jump leads to the documentation of the deliverable.

Although this general framework is adopted for modelling both outcomes O1 and O2, they have different nature, and thus some steps can be not suitable for a specific outcome.

Outcome O1, namely a technology stack in the form of a reference model, has a purely literary basis. Literature classics and recent literature reviews are used to define well-established knowledges and discover research gaps or unsuccessfully faced threads: literature databases as Scopus[13], Google Scholar[14] have been queried for discovering and retrieving documents and studies useful for this thesis directly on the web, and also NILDE interlibrary consortium within the IDEM federation joined by University of Parma is used for retrieving suitable materials and studies not available on the web. A systematic literature review of previous studies covers the whole 'Model Mapping' jump as well as the 'selection and combination' step of the 'Model Prototyping' jump. The validation and verification of the model has still literature basis, namely the reference model is tested through its compliance with characteristics of reference architectures for I4.0. On the other hand, outcome O2, namely a maturity model to detect the compliance of SME businesses with I4.0 novelties, is the real experimental part of this thesis and it involves local companies to map their current business principles, and to design consistent evolution paths towards I4.0. This part has been carried out in partnership with CISITA scarl[15] and SMILE DIH[16], within the research project "*Individuazione delle soluzioni tecnologiche abilitanti e modeling delle competenze richieste nella filiera alimentare della provincia di Parma*", project CIG 7817647E60[17]. The project has been funded by Fondirigenti[18], the Confindustria[19] and Federmanager[20] consortium' fund, that promotes and funds continuous training plans to increase Italian managers' skills and adapt them to the challenges of global competition. In this case, a systematic literature review allows (i) to map the state-of-the-art of maturity models in industry, and (ii) to select techniques and tools to develop a new model ('Model mapping'). A field survey, by means of unstructured interviews (Burgess, 2002) involving SMEs entrepreneurs and managers provides the 'external proposition and ideas ('Model mapping'). The same SMEs involved in the project, constitutes the environment in which the maturity model is verified and validated. This last step covers also methodology adopted for answer to the research question RQ3 and provide the outcome O3. The contribution of this thesis to the scientific research especially lies in combining two models that have been not used holistically yet, as it emerges in the rest of the thesis.

For designing the models, systems design tools and architecture framework set of practices are used, and applications and software for diagramming and computing as well. Figure 1.2 explodes methods adopted for conducting the research, and relative means, i.e. techniques and tools.

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[11] As defined within the norm UNI EN ISO 9001:2015, retrieved from https://www.certificazionequalita9001-2015.it/ufaqs/che-cose-il-ciclo-di-deming-o-pdca/. Last access: 2020/07/29

[12] As defined in EEE Draft Guide: Adoption of the Project Management Institute (PMI) Standard: A Guide to the Project Management Body of Knowledge (PMBOK Guide)-2008 (4th edition)," 2011. Retrieved from https://ieeexplore.ieee.org/document/5937011. Last access: 2020/07/29

[13] https://www.scopus.com/search/form.uri?display=basic

[14] https://scholar.google.it/

[15] https://www.cisita.parma.it/

[16] https://www.smile-dih.eu/?lang=en

[17] https://www.smile-dih.eu/fondirigenti-digital-skills-for-the-food-industry/?lang=en

[18] https://www.fondirigenti.it/

[19] https://www.confindustria.it/en

[20] https://www.federmanager.it/

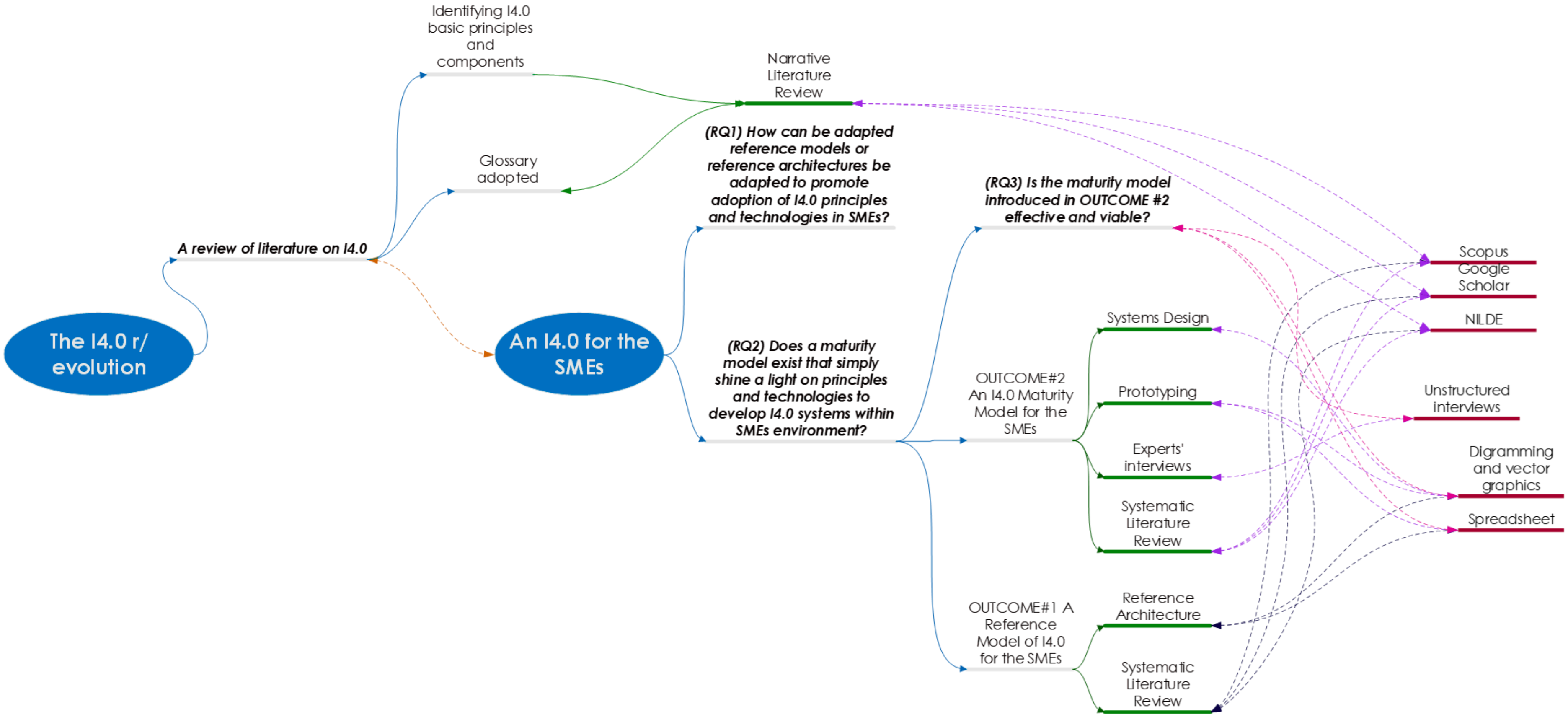

Figure 1.2. Methods, techniques, and tools used in this research

Blue arrows link the RQs and outcomes of the research with the research triggering core topic. Green arrows link the outputs with the methods adopted (standing on green shelves). Dashed arrows, in different shades of magenta for a better identification of connection, link techniques and tools (standing on crimson shelves) to the methods that involve using them.

It is noted that dashed orange-arrow link the stage of identifying basics of I4.0 principles and components with the stage of modelling thesis outcomes. They stress the preparatory role of selecting I4.0 basics: results achieved in this stage are the inputs for the suitable modelling of outcomes.

1.5 Structure of this thesis

To conclude the big picture of this thesis, in this section it is provided its reminder.

Chapter 2 proposes principles and components of the I4.0, rearranging them in a suitable manner for SMEs, i.e. in a simplified functional view. It mainly starts by literature classics, however considering also recent relevant literature, selected on the basis of relevance to academia (i.e. number of citations over the years) and consistence of contents retrieved by either directly querying literature databases or indirectly reading papers that refer to that contents. Thus, it is structured as the literature review section on I4.0. A framework for I4.0 is designed. The framework is structured as a synthesis of previous work and wants to describe in a simplified and clear manner how the I4.0 is fostering the r/evolution of the industrial systems. With this purpose, the industrial system is viewed as a black box, whose inputs, resources, and constraints are used to depict a value stream map of the I4.0. Inputs are identified as considered in the traditional business view. Resources and constraints are those brought by the I4.0 from both technology and business, and social-political-economic point of views. The output is a new industrial paradigm which leads to a set of fundamentals which are the essential features of I4.0, to derive few but necessary elements of the I4.0 technology and business stack. This process has been judged necessary since it is supposed to be useful for disseminating a complex phenomenon bringing lots of novelties in technology integration and BMs development, as the I4.0 actually is. In fact, although largely debated from various sources, often companies have not a clear idea of what I4.0 is (Eisert, 2014), and they strive to identify what they need for getting I4.0-compliant[21]. This is truer in the SMEs environment, often unprepared to grasp their opportunities, as previously discussed. Furthermore, since the vast amount of literature developed by different authors, countries and affiliations, subject areas, and research fields, in addition to the fact that the research topic is relatively new, vocabularies used among researchers are inconsistent. This issue is solved providing a glossary which sets meanings as conveyed in this thesis.

Chapter 3 provides the first outcome of this thesis. The usefulness of structuring the characteristics of I4.0 by means of reference instances is assessed. Next, with the aim of describing how to design a reference instance considering the crucial elements of I4.0, one of the most important architecture towards this goal (Hankel & Rexroth, 2015) is analyzed, i.e. the Reference Architectural Model Industrie 4.0 (RAMI 4.0) of VDI/VDE-Gesellschaft Mess- und Automatisierungstechnik[22]. Further, a systematic literature review of reference architectures and models in I4.0 is developed, for identifying gaps to fill in towards a clear comprehension of I4.0 basics. Finally, the reference model pursuing this purpose is

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[21] Source: Gfk Enigma, "Umfrage in mittelstandischen Unternehmen zum Thema Digitalisierung - Bedeutung für den Mittelstand", *Study ordered by DZ Bank*, 2014. Retrieved in Rajnai and Kocsis (2018)

[22] VDI/VDE-Gesellschaft Mess- und Automatisierungstechnik. StatusReport. Reference Architecture Model Industrie 4.0 (RAMI4.0). July 2015. Retrieved from: https://www.zvei.org/fileadmin/user_upload/Presse_und_Medien/Publikationen/2016/januar/GMA_Status_Report__Reference_Archtitecture_Model_Industrie_4.0__RAMI_4.0_/GMA-Status-Report-RAMI-40-July-2015.pdf

designed in its implementation view, since the will to entail technologies that are needed for the implementation of the functional components defined in the functional framework. Chapter 4 proposes a maturity model to survey how SMEs of the ER region are responding to the evolving industrial scenario towards the I4.0. In particular, the study focuses on the Parma district, where the research has been carried out. In this area, the food & beverage and the mechanical engineering industries are predominant[23]. Although lots of maturity models have been designed and discussed in academic and practitioners' literature, it is demonstrated that models entailing SMEs and processing industry characteristics lack and are generally designed towards mapping the company maturity onto tradition LEs characteristics. Once that the basics of the theory of maturity model and the review of maturity model in I4.0 are provided, a new maturity model is designed, taking into considerations all aspects neglected by previous studies. Finally, some case studies are proposed to better understand how it works and its wherewithal to support SMEs in defining new BMs towards their own I4.0 evolution.

Chapter 5 is devoted to discussing the insights to the proposed work, and to the interpretation of results towards future works.

provides a brief recap of the thesis structure.

Figure 1.3 maps chapters of the thesis by means of a flowchart.

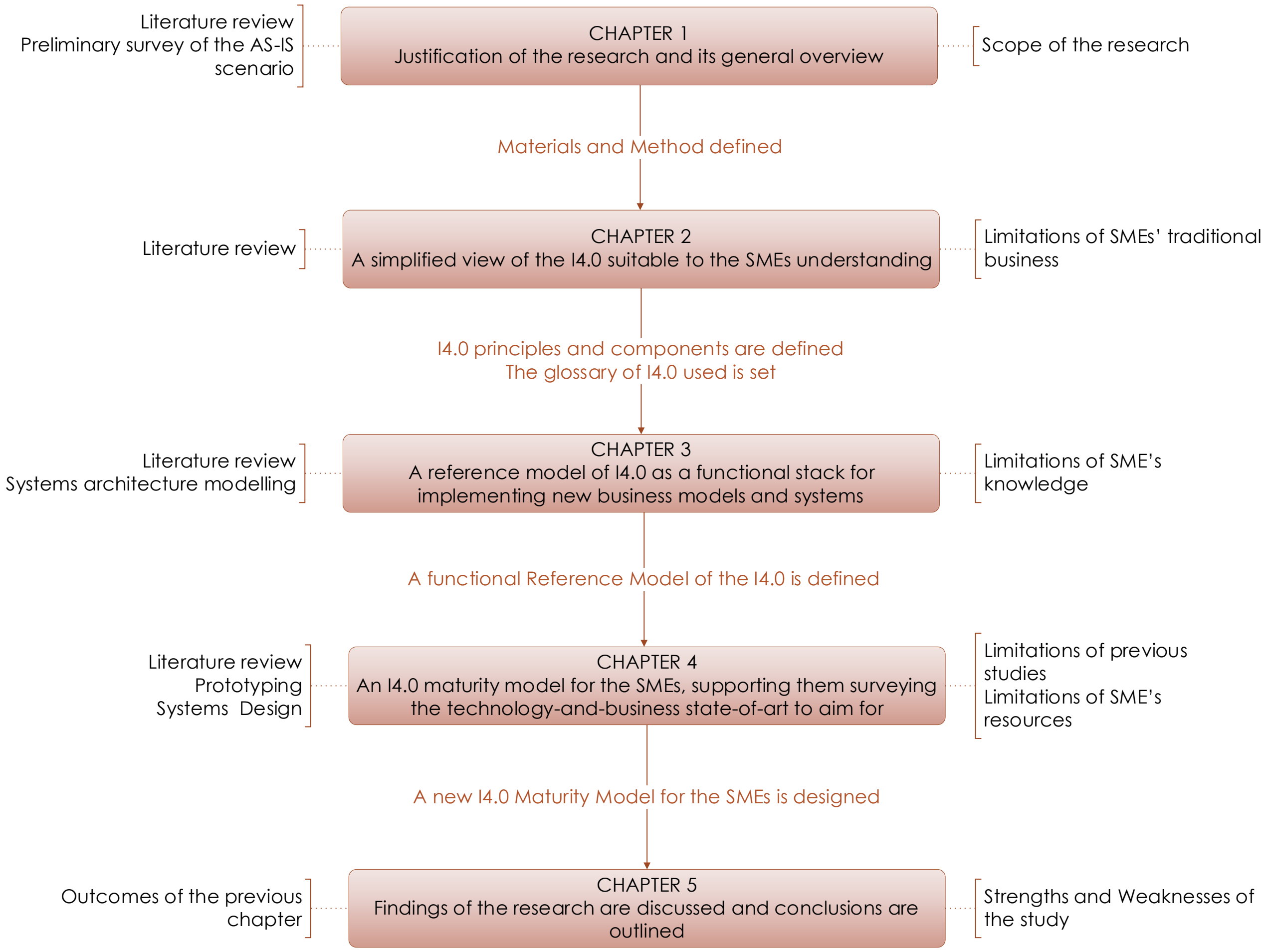

Figure 1.3. Graphical reminder of the thesis

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[23] Source: http://www.parmalimentare.net/it/chi-siamo/territorio/. Last access: 2020.08.01

Each chapter is considered as a black box enclosing materials and contents, inputs and outputs relate to the research proposals and findings, respectively, while resources (on the left of the flow line) and constraints (on the right of the flow line) relates to materials and methods as previously introduced.

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2 The Industry 4.0 r/evolution

Academia and practitioner's world both have made efforts to describe what is I4.0 (Mueller, Chen, & Riedel, 2017), and especially to design principles for shaping I4.0 scenarios in real companies (Hermann et al., 2016). As a consequence, a huge amount of literature on the related topics has been produced, as (i) scientific publications for the academic community, (ii) white papers[24] in government or marketing initiatives, (iii) grey literature[25] with the aim of delivering I4.0 principles to the practitioners' world, (iv) and other possible channels of communication. The truth of this statement is provided in the following, where all quantitative results refer to date of writing this dissertation, of course. As a matter of fact, by querying Google, the most used search engine in the world[26], about 'Industry 4.0', it gives more than 416 million items, through web worldwide domains. Since the complex of principles identified with the I4.0 relates to the fourth industrial revolution as the mass production principle relates to the second industrial revolution (Yin et al., 2018), to verify that the term 'Industry 4.0' is nowadays a real buzzword, the result of the query is compared with the term 'Mass Production' by using the same search engine. The output is about 1,200 million items, which is a result close to three times the previous. However, by focusing on the seniority of the terms, the latter result relates to a term over 100 years old, while the term Industry 4.0 is still not a teenager! Narrowing the sources to just the scientific research dissemination, it is possible to refer to all forms of scientific literature or to just academic publications. In the former case Google Scholar (https://scholar.google.com) gives more than 16,000 items, while in the latter Scopus (http://www.scopus.com) provides about 8,000 results, mostly belonging to engineering field (i.e. about 30% of the total). Indeed, the difference between these databases lies on the fact that Scholar entails non-academic sources too (Mikki, 2010). I refer to these databases since they are some of the most important bibliographic databases (Cobo, López-Herrera, Herrera-Viedma, & Herrera, 2011). Figure 2.1 briefly recaps the even increasingly interest of academic community, especially the engineering one, to I4.0. Both pictures were retrieved from Scopus to date of writing this dissertation. The query is limited to timespan 2012-2019 to comply with both needs for (i) considering the chronologically first citation of I4.0 in the Scopus database, and (ii) avoiding affecting the result by the intermediate results of 2020. Scopus is preferred to Google Scholar for these evidences because the latter does not provide statistics and trends (Mikki, 2010), but it does not mean that non-academic sources are not suitable for this dissertation. In fact, these sources are also used in the following.

Although these widely recognized efforts, the common results on the research of I4.0 are criticized since they are either too general to put into practice, or by the contrast too detailed to focus on one specific environment (Oesterreich & Teuteberg, 2016). As largely debated in the introduction of this dissertation, these aspects are critical when dealing with designing applications for the SMEs, since they are supposed to refuse or abort projects developing I4.0 systems and applications, because of two reasons: they deem I4.0 to be too challenging, or they fail to understand I4.0 and its novelty.

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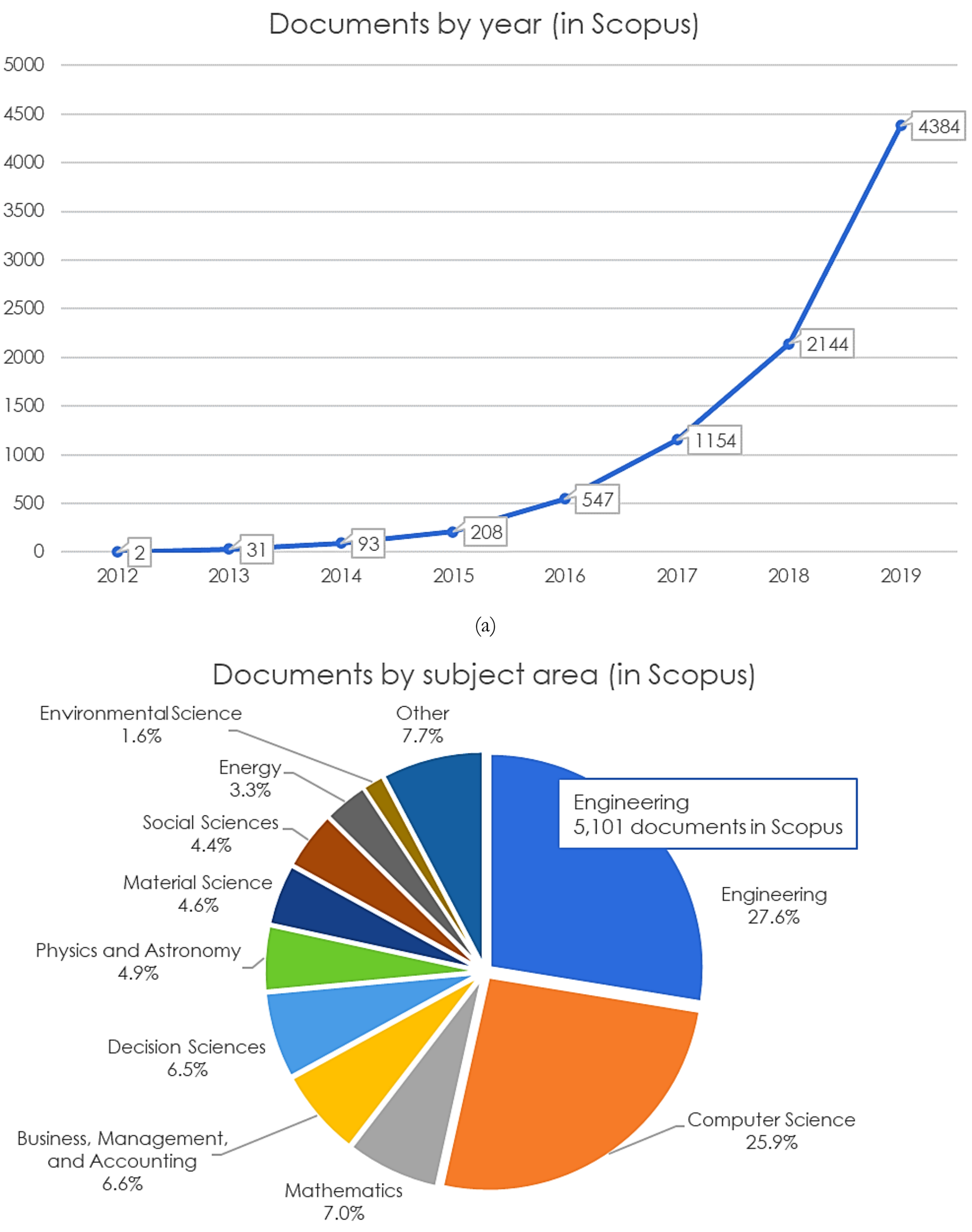
[24] For full definition, refer to https://en.wikipedia.org/wiki/White_paper. Last access: 2020.01.22

[25] For full definition, refer to https://en.wikipedia.org/wiki/Grey_literature. Last access: 2020.01.22

[26] Source: https://www.reliablesoft.net/top-10-search-engines-in-the-world/. Last access: 2020.01.23.



(a)

(b)

Figure 2.1. Use of the term 'Industry 4.0' over 2012-2019 timespan in Scopus: (a) number of citations and (b) research field clusters. Values of 2019 and Engineering field are highlighted. Graph replies artwork of Scopus tool "Analyze search results"[27] [28]

Another aspect descending from the huge amount of literature produced on I4.0 is about vocabulary inconsistencies used among (i) different nations and languages, (ii) different backgrounds of people interested in I4.0, and (iii) different research fields. In fact, lots of actors have developed studies on I4.0 discussing topics of interest to this dissertation, namely, how to implement I4.0 principles within

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[27] Source: https://www2.scopus.com/term/analyzer. Note that just the link visualisation has been modified for the sake of the footnote layout, nevertheless the URL actually works indeed. Last access: 2020.01.23.

[28] The query string is TITLE-ABS-KEY ("industry 4.0")

industries, as well as the advantages and the risks that the effort to develop a fully I4.0-compliant systems brings. However, due to their very diversity, there still is much confusion on vocabulary and topics relating to I4.0, as some examples in the following show. For instance, as stated by Bertolini et al. (2019) the terms 'Industrie 4.0' and 'Industry 4.0' are often confused. However, the former refers to the German government initiative within a national program to secure German manufacturing industry. This initiative has been followed by other subjects in the world, e.g. 'Factories of the Future' within the program Horizon2020 of the European Commission, as it is also mentioned in the introduction. Instead, the term 'Industry 4.0' was introduced in scientific research and it has become widespread in society since there is a general consensus that the speed and impact of these development led to the fourth industrial revolution (Schwaab, 2015), even though the individual changes in the manufacturing sector can be interpreted as just an evolution of the current industrial scenario (J. Lee, Kao, & Yang, 2014). Furthermore, there is still confusion between the term 'Industry 4.0' and the term 'Industrial Internet', i.e. it is not clearly defined which term has a more holistic vision, and sometimes they are used alternately. For examples, see the study of Drath and Horch (2014), Hermann et al. (2016), and Wang et al. (2016). A valuable contribution to address the difference comes from Thoben Wiesner, and Wuest (2017). The authors of that study distinguish between the two terms by identifying 'Industrial Internet' as a complex of principles more oriented to the manufacturing systems, designed with the aim of responding to the 'Industry 4.0' revolution, meant as complex of principles addressing changing in business, market and operations. Furthermore, the Industrial Internet should not be confused with 'Industrial Internet of Things' (IIoT), the IoT sub-paradigm emerged at a later time and focusing on the interconnectivity of industrial assets (L. Da Xu, He, & Li, 2014). Same confusion exists concerning the difference between CPSs and 'Cyber-Physical Production Systems' (CPPs), which are technology-focused frameworks solving limitations that otherwise really confine the possibilities of CPSs in production environment (Verl, Lechler, & Schlechtendahl, 2012). These authors identify these constraints with the (i) limited computing hardware resources, and (i) the lack of interfaces that allow communication among assets. The real misunderstanding is furthermore highlighted by the fact that, as technology focused frameworks, the concept of CPPS is actually more similar to the concept of IoT than the CPS one (Bruner, 2013).

The aim of this chapter is to provide the reader with a twofold review of the literature on I4.0. In the first section, an in-depth analysis of literature classics and literature relevant to this dissertation is provided. The specific goal is to define elements characterizing I4.0, namely elements for a technology stack and new industry paradigms. The second section deal with providing a glossary of main recurrent terms of I4.0, and their meanings to this thesis. The glossary, as well as the insights provided, do not criticize uses of the terms as made in other scientific literature, rather than it aims to support the reader in the clear comprehension of concepts as interpreted in this study, and developed in the following chapters. Once that elements of I4.0 and the lexicon adopted has been provided, third section of this chapter draws a framework of I4.0 leveraging its basics previously identified. Finally, in section four, conclusions are provided about what has been achieved in this chapter and how it will be further used in this thesis.

2.1 An Industry 4.0 map

Considering industry as a core element of the value chain and a crucial component in the technological development, job creation and economic stability of a country (Kim, 1980), the I4.0 can be viewed as a fundamental strategy to confront new requirements in the global market and position industries more competitively against other countries (Blanchet, Rinn, Von Thaden, & De Thieulloy, 2014). Ever increasing global competitive pressure, shrinking product lifecycles and fast changing technologies are driving companies, towards networking to remain in competition (X. L. Chen, 2014). Networking not only refers to the collaboration of companies within the supply chain, but also to the IoT system implementation, which in manufacturing is the complex interconnection and collaboration of (i) robot, machine and workers within the workshop, and (ii) individual players within the whole production systems (Hermann et al., 2016; Mueller et al., 2017). As a result, manufacturing in I4.0 consists of exchanged information and controlled machines and production units acting autonomously and intelligently based on information networked (Hermann et al., 2016; Oesterreich & Teuteberg, 2016; Qin, Liu, & Grosvenor, 2016). If the wide interconnection among industry partners and components offers new potential to the manufacturing industry such as meeting individual customer requirements, optimizing decision-making and adding new product capacities (Kagermann et al., 2013), on the other hand it means that boundaries among these objects would be weakened, allowing the needed flow of information to be collected and communicated autonomously for the intelligent support of decision maker (Mueller et al., 2017).

The intense use of ICT and especially the rise of the Internet of Things (IoT), allowing the industry networking, promote the digitalization of manufacturing (Kassner et al., 2017), which leads to an increasingly, large amounts of industrial data, namely the industrial Big Data (BD) (Kemper, Baars, & Lasi, 2013). BD include both structured and unstructured industrial contents, as machine sensor data on the shop floor, failure reports written by service technicians, product usage data directly from the end customer, as well as customer complaints data from social networks. The IoT allowing to collect BD from which to extract valuable business insights and knowledge enables the vision of I4.0 (Brettel, Friederichsen, Keller, & Rosenberg, 2014; Gölzer, Cato, & Amberg, 2015).

According to Kagermann et al. (2013), digitalization and networking of the fourth industrial revolution are realized through three main components and three integrations within eight priority area for action. Main components are CPS, IoT and IoS, and SF, which are already introduced in the first chapter of this thesis. The mentioned three integrations are the horizontal integration, the vertical integration, and the end-to-end engineering integration. An in-depth analysis of these elements is provided in next subsection, in which their genesis and evolution is reviewed together with a review of enabling technologies of I4.0. Finally, eight priorities are clustered into three upper containers according to Liao et al. (2017):

- IT-based deployment
  - Standardization and Reference Architecture: *"development of a single set of common standards to support collaboration and of a reference architecture to provide a technical description of these standards"*.
  - Delivering a Comprehensive Broadband Infrastructure: *"development of a reliable, comprehensive and high-quality communication network to expand the broadband Internet infrastructure in a massive scale"*.
- Manufacturing Operation Evolution
  - Managing Complex Systems: *"development of appropriate planning (for systems to be built) and explanatory models (for existing systems) to provide a basis for managing complex products and manufacturing systems"*.
  - Work Organization and Design: *"implementation of a socio-technical approach for work organization and design to offer workers the opportunity to enjoy greater responsibility and enhance their personal development"*.
  - Training and Continuing Professional Development: *"realization of appropriate training strategies and organization of work in a way that fosters learning, enabling lifelong learning and workplace-based Continuing Professional Development"*.

  - Resource Productivity and Efficiency: *"to deliver gains in resource productivity and efficiency. The calculation of the trade-offs between the additional resources that will be needed in smart factories and the potential generated savings".*
- Regulation Changeability
  - Regulatory Framework: *"mutual adaptation of new innovations with existing legislation. The protection of corporate data, liability issues, handling of personal data and trade restrictions".*
  - Safety and Security: *"to ensure that production facilities and products themselves do not pose a danger either to people or to the environment. Meanwhile, protect the data that they contain against misuse and unauthorized access".*

However largely debated, a big gap can still be found in providing a bridge between state-of-art in theory and state of practice in companies since a mismatch between academia and practice influencing the identification of challenges and requirements for the application of I4.0 (Mueller et al., 2017).

Next reviews of literatures on I4.0 is focused on (i) basic concepts (i.e. triggers, requirements, outcomes), and (ii) enabling technologies. Review entails I4.0 description from both abstract and technical level. Then, it is drawn a framework simplifying functional view of I4.0 to its basics. Functional view is preferred to other views, since addresses the functional components of the system and interaction between these components and with external elements to the system (Unverdorben, Böhm, & Lüder, 2018). The first part of the review is devoted to identifying constraints and outputs of the framework. Then, the second part deals with defining the inputs and resources for facing and realizing the previously identified constraints and outputs, respectively.

2.1.1 An abstract level description of I4.0

I4.0 is the industrial and academic answer to cope with challenges of the fourth industrial revolution (i.e. global competitive pressure, shrinking product lifecycles and fast changing technologies). A general overview on I4.0 is provided by Lasi et al. (2014) one of the most important and cited work about the fourth industrial revolution (Muhuri, Shukla, & Abraham, 2019). Lasi et al. (2014) discussed the I4.0 as the main component of this fourth industrial revolution, which creates a sound base for the evolution and variations in the manufacturing systems. The paper also defined I4.0 basic concepts and its real applicability in the modern industry (Muhuri et al., 2019). In the following, the description of I4.0 as emerges from the work of Lasi et al. (2014) is provided, then the picture depicted by these authors is deepened by other useful studies for the sake of a comprehensive description of I4.0 principles and outcomes, however simple and clear keeping in mind the suitability of such a description to the SMEs.

The root of the I4.0 lies in socio-economic and political changes: (i) short development periods, (ii) individualization on demand, (iii) business trend towards switching from product to service-orientation, (iv) flexibility, (v) decentralization, and finally, (vi) resource efficiency. Both an intensive 'technology push' in industrial practices, by all fields of engineering, and new industrial paradigm towards new business principles are the response to these changes. If networking and digitalization are already introduced in the section before, and next section provides an in-depth analysis on technologies suitable for developing a networked digitalization of companies, the analysis on paradigm and principles carried out by Lasi et al. (2014) is worth a mention to draw a big picture of I4.0.

I4.0 proposes (i) a new paradigm shift in industrial production, (ii) modular and efficient manufacturing systems, and (iii) products able to control their own manufacturing processes.

New paradigm concerns the 'individual production batch size of one piece in still economic conditions of mass production'. The even increasing customization descends from the possibility of integrating individual needs into the manufacturing system (Dominici et al., 2016). This leads to the 'mass customization' which aims to deliver products and services that best meet individual customers' needs with near mass production efficiency (M. M. Tseng, Jiao, & Merchant, 1996). The capability of achieving 'even one-off items' with profit is directly linked to the more flexibility to achieve[29]. Flexibility is defined as the ability to respond to markets demands by policies and actions that allows quickly switching between one product and the others (Nemetz & Fry, 1988). Also, batch size customized on the basis of client' demand is linked to adding service features to the product, since the servitization is the client-centric view of making business, as it emerges from Roy et al. (2009). These aspects require new systems in distribution, procurement, and development of product and services to cope with individual production batch and logistic unit. Moreover, servitization is further stressed in the digitalization era as 'Digital Servitization', namely the encapsulation of digital services within physical products (Vendrell-Herrero, Bustinza, Parry, & Georgantzis, 2017).

Modularization and streamlining for manufacturing systems concerns the capability of facing shorter product life cycle and 'last minute changes', as well as 'corporate social responsivity' towards resource efficiency. Modularization is a product design approach where the product is assembled from a set of standardized constituent units suitably designed, thus different assembly combinations from a given set of standardized units ends with different end-product models and variations (Starr, 1965). With this regard, modularization positively affects flexibility (Ernst & Kamrad, 2000). Resource efficiency copes with efficient manufacturing systems, the environmental sustainability and the adaptation to human needs (Drath & Horch, 2014; Roblek, Meško, & Krapež, 2016). New requirements of systems for flexibility, efficiency, sustainability, descends from the fact that current production paradigm is not sustainable yet (Alkaya, Bogurcu, Ulutas, & Demirer, 2015). Finally, humans moved from the role of operators to the role of decentralized unit manager (Hermann et al., 2016), needing to acquire even more IT and business management skills (Günther Schuh, Anderl, Gausemeier, Ten Hompel, & Wahlster, 2017). Decentralization relates to the ability of local actors (companies, specialists as well as workers, or machines) to make decisions with employing specialized knowledge, aiming to achieve self-organization outside conventional hierarchies (Roblek et al., 2016).

The view of a product controlling its own design and production process leads to the concept of smart product (SP) (Zawadzki & Żywicki, 2016), which also adds the feature of acquiring data from the end-customer and sharing these with industry for its improvement (Porter & Heppelmann, 2014)

The final outcome of these whole system is the value-creation network, which means an inter-company connectivity between suppliers and customers within the value chain (Müller et al., 2018).

2.1.2 State-of-the-art of research on enabling technology

Especially automation and data exchange allows to cope with I4.0 industrial paradigm and grasp the expected benefits (Grangel-González et al., 2016; Rojko, 2017). All engineering fields are involved in the I4.0, with a real 'technology-push' for spreading applications (Lasi et al., 2014). With this regard, the exploration and introduction of enabling technologies of I4.0 is a real research stream (Posada et al., 2015). Centrality of technology as trigger for the fourth industrial revolution lies on the fact that emerging

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[29] Federal Ministry of Education and Research (BMBF). Project of the Future: Industry 4.0. Available from: http://www.bmbf.de/en/19955.php. Retrieved in: Mueller et al. (2017).

technologies are affecting manufacturing models, approaches, concepts and even businesses, that are leading the same revolution (Zhong, Xu, Klotz, & Newman, 2017). Interpreting (Rojko, 2017), this revolution is technically an expansion of the previous third industrial revolution by adding to the pushed digitalization of manufacturing the development of ICTs to leverage CPS via IoT for realizing SFs, coherently with the work Kagermann et al. (2013). CPS is defined as new generation of systems with integrated computational and physical capabilities that can interact with surrounding physical world and expand the capabilities of the same physical world through computation, communication, and control (Baheti & Gill, 2011). In this sense, CPS can be considered as an extension of Digital Twin (DT) (Tao, Qi, Wang, & Nee, 2019), as the former technology allows to add new capabilities to physical systems using computation and communication intensively interacting with physical processes (L. Wang, Törngren, & Onori, 2015), while DT provides a comprehensive physical and functional description of a component product or system (Söderberg, Wärmefjord, Carlson, & Lindkvist, 2017). IoT refers to interconnected systems in a networking world in which various objects are embedded with electronic sensors, actuators, or other digital devices, so that they can collect and exchange data (Xia, Yang, Wang, & Vinel, 2012). The genesis of IoT is automatic identification (auto-ID) technology that firstly allowed to introduce the concept of smart objects (Tao et al., 2019). Via the interconnection of smart objects, SF enables companies with flexibility, efficiency, and effectiveness (Mueller et al., 2017). According to Miragliotta, Perego, and Tumino (2012), and Hopf et al. (2014), the main characteristics for interpreting the term ‘smart’ are: (i) integrated functions for identification, localization and diagnosis of internal parameters; (ii) capability to detect physical data and measuring the performances; (iii) capability to process data for the gaining relevant information; (iv) capability to interact with other smart objects and centralized information system; (v) standardization and uniformities of protocols; (vi) openness for accessibility; (vii) multi-functionality for different applications. Research on SFs were firstly performed in the second half of the first decade of 2000’s by the German Center of Excellence Nexus (SFB 627) of the Institute of Industrial Manufacturing and Management (IFF), and has been formally introduced by (Lucke, Constantinescu, & Westkämper, 2008) as “*a factory context-aware assists people and machines in execution of their tasks*”: the SF enables real-time collection, distribution and access of manufacturing relevant information anytime and anywhere.

IoT is the technical infrastructure for the realization of Cyber-Physical Systems (Oks & Fritzsche, 2015), and CPSs are the backbone of SF since they provide it with rea-time capabilities (Hozdić, 2015): Cyber-Physical System via IoT can not only help to map physical systems to virtual world, but also retrofitting the physical operation and process control with virtual digital system, realizing the fusion between real and digital world part of the SF (Hopf et al., 2014). On the other hand IoT and SF are directly linked to another couple of technology: BD and Big Data Analytics (BDA), somehow used interchangeably, for identifying the even more increasing access to data from many different sources, and their synthesis to support real-time decision making (Rüßmann et al., 2015), are generated by ‘cyber-machines’ and ‘cyber-operator’ via IoT (Mourtzis, Vlachou, & Milas, 2016). What this first view of I4.0 lacks with respect to the picture provided by Kagermann et al. (2013), is the IoS. The IoS is the use of computing infrastructures for developing and delivering platform and software applications and leverages cloud computing for provisioning models for on-demand access to applications (Moreno-Vozmediano, Montero, & Llorente, 2012). It’s clear that IoS, as belonging to the Internet of Everything concept, is strictly linked to the IoT which provides infrastructure, to connect things, objects, and data to be exploited by new way of performing processes and businesses (Hermann et al., 2016).

IoT and BD/BDA as ICTs (Aceto, Persico, & Pescapé, 2019), and CPS and SF as manufacturing technologies (Muhuri et al., 2019) are the real fundamentals of main studies on enabling technologies of I4.0, and they are more or less always cited as I4.0 enablers, beyond the fact that they are somehow directly mentioned by Kagermann et al. (2013) as I4.0 components. Other studies introduced several technologies as I4.0 enablers, sometimes introduced as technology trends or technological advancement (Rüßmann et al., 2015), sometimes as technological groups (i.e. technologies and methods) (Moeuf et al., 2018); other times enabling technologies mixes up technology paradigms, research fields, and real technologies or their specific applications (Aceto et al., 2019). However, it is possible to identify clusters of technologies according to specific fields or applications for which they are selected. For instance, Aceto et al. (2019) have proposed an huge survey on ICTs for Industry 4.0 focusing on just technology aspects and considering ten technological enablers. Beyond BD and IoT, they have identified Fog and Mobile Computing, Artificial Intelligence, Human-Computer Interaction, Robotics, and other somehow taken for granted as Open-Source Software, Blockchain, and the Internet. In the same field, Xu et al. (2018) together with CPS and Cloud Computing, have exploded two technologies. Firstly, IoT technologies: they have identified as its components (i) Radio Frequency Identification (RFID), (ii) Wireless Sensor Network (WSN), and (iii) Ubiquitous computing. Secondly, Industrial Integration, enterprise architecture, and enterprise application integration: they have identified the following components: (i) Service-Oriented Architecture (SOA), (ii) Business Process Management, and Production and Operation Management, and (iii) Information Integration, and Interoperability. Saucedo-Martínez et al. (2018) have analyzed nine prominent technologies addressing the I4.0 in management and operations: beyond BDA and IoT applied to the industrial context (i.e. Industrial IoT, also IIoT), they have identified Autonomous Robots, Simulation, Horizontal and Vertical System Integration, Cyber-Security, Additive Manufacturing, Augmented Reality, and the Cloud. In this field, S. Wang et al. (2016) have identified Artificial Intelligence technologies (e.g. Multi-Agent Systems) beyond IoT, BD, and Cloud Computing, to be integrated with industrial automation, business, and trade, for enabling I4.0. Again in industrial systems management, Moeuf et al. (2018) have identified Simulation, Cloud Computing, Virtual Reality, Cyber Security, Collaborative Robots, and Machine-to-Machine Communication, beyond BDA, IoT, and CPS. Finally, among other studies dealing with identifying enabling technologies, here is cited the study of Rüßmann et al. (2015), who identified nine technology pillars for manufacturing and production: these are BDA, Autonomous Robots, Simulation, Horizontal and Vertical System Integration, IIoT, Cybersecurity, Cloud (Computing), Additive Manufacturing, and Augmented Reality. This list, although does not substantially differ from others, is worth to mention since it has been generally recognized in practitioners' world[30].

2.1.3 An overview on total integration

The term integration refers to the act of bringing together smaller components into a single system that functions as one, and in IT context is a process that ends with merging together different subsystems so that the data contained in each becomes part of a more comprehensive system quickly accessing and sharing data when needed[31]. Although somewhere approached as technology, total integration is a concept of I4.0. It is a real key for transition from 'linear value chain' to an 'automated and highly dynamic value network', including production systems, infrastructures, and customers, ideally completing the

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[30] Visit https://www.bcg.com/it-it/capabilities/operations/embracing-industry-4.0-rediscovering-growth. Last access: 2020.08.23

[31] For a full definition: https://searchcustomerexperience.techtarget.com/definition/integration. Last access: 2020.08.24

automation of the whole production processes (Davies, 2015). As a consequence, integration is the most crucial aspect in the I4.0 strategy (Mueller et al., 2017). Smart networks for integration are established under CPS and pursue four types of total connectivity: (i) between people, (ii) between people and machines, (iii) between different machinery and equipment, and (iv) between different software services, allowing the network architecture to achieve extensive integration at the horizontal, vertical, and terminal-to-terminal levels (J.-Y. Chen, Tai, & Chen, 2017). The connectivity of assets and capacity of sharing data at every point through integration, in the perspective of Iordache (2017), allows companies to connect the customers' needs to supply chain and to production equipment and operators, namely the smart manufacturing. In the view of Hermann et al. (2016) the whole interconnection among assets represents two of main design principles of I4.0, out of four: 'interconnection' properly, and 'information transparency' which leads to context-aware information for appropriate decisions.

As previously introduced, total integration has three forms: horizontal integration, vertical integration, and end-to-end engineering integration (Kagermann et al., 2013). S. Wang et al. (2016) have focused on the vertical integration to implement flexible and reconfigurable smart factory by means of a system architecture composed of (i) physical resources, (ii) industrial network, (iii) cloud, and (iv) devices for controlling the system. However, in their work authors have provided a meaningfully description of three integrations of I4.0. The horizontal integration is the inter-corporation integration to form an efficient ecosystem through collaboration, aiming VNs. The vertical integration allows the communication amongst assets within the corporation, both physical (e.g. machines, devices) and informational (e.g. ERP, MES) to form a self-organized system which is flexible and reconfigurable by exploiting traditional automation pyramid. According to the analysis of Hermann et al. (2016), this vertical integration, realized via IoT and CPS, allows to specifically tackle two other design principles of I4.0, namely 'decentralized decisions' and 'technical assistance'. Finally, the end-to-end engineering integration is the key enabling a product-centric value creation process, addressing product design and development, services, maintenance, and recycle. This transparency over the manufacturing process, allowed by end-to-end engineering, is also potential to facilitate optimized decision-making[32].

2.1.4 Results

SF as component of the fourth industrial revolution are realized by exploiting digitalization of assets and processes, and networking physical and informational systems. The goal of SF is to cope with the changing market and industrial scenario, which is even more asking for flexibility, efficiency, sustainability, with transparent interconnection of systems and increasingly aware decision-making. Total integration of systems, i.e. horizontal integration, vertical integration, and end-to-end engineering integration faces these issues towards a value-creation network for businesses. Keeping in mind three directions to which BMs of I4.0 aim, introduced in the previous chapter, it is possible to link all of them to the concepts of integration. Open Innovation is possible to be realized horizontally integrating the system: horizontal integration, in fact, connects the SF to all stakeholders (i.e. suppliers and customers), and to the SPs produced by the SF itself. Networked Manufacturing System is realized through vertical integration, which connect in efficient and agile way all subsystems of the SF. Finally, end-to-end engineering links the "voice" of the customer about the product to the product itself and then to its development, realizing together with horizontal integration, the Service Design. These directions are then realized especially by means CPS and IoS (as part of IoT), but more in general three main technologies

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[32] Federal Ministry of Education and Research (BMBF). Project of the Future: Industry 4.0. Available from: http://www.bmbf.de/en/19955.php. Retrieved in: Mueller et al. (2017).

can be considered as backbone of SFs: the IoT realizing the network among elements, the BD and BDA that spread via IoT and generates the information for managing and retrofitting assets of the system arranged as a complex of CPSs. These three technologies are enough to provide a general functional view of I4.0 from technical standpoint, and introducing other technologies sounds fuzzy since their selection depends either on the field of research, or on the specific industry. For instance: what does it means talking about Additive Manufacturing technologies as I4.0 enabler in the processing industry?

I4.0 principles and technologies, such as modularization, flexibility, decentralization, as well as digitalization and networking, are well-established in manufacturing and engineering. However, the I4.0 spread of utilization of these technologies, and the intensive exploitation of these principles have let (and is letting) a technical evolution of industry (and manufacturing) that has the outcome of a revolution in the way of making business.

2.2 Glossary used in this thesis

In the previous sections, lots of I4.0 elements have been introduced. Other are neglected, even if of interest to I4.0. However, these elements are not directly of interest to this thesis since they either belong to research field or applications out of scope of the analysis carried out. Nevertheless, definitions of terms consistent to the view of the present study is provided, for the sake of a clear comprehension of the big picture the thesis wants to depict. Since the widespread of I4.0 leads to a huge number of terms referred to I4.0, this glossary considers main recurrent terms used within I4.0 dissemination and its fundamentals. The main components and features of I4.0 according to Kagermann et al. (2013), and the central paradigm explaining the vision of I4.0 according to Weyer, Schmitt, Ohmer, and Gorecky (2015). These elements are listed in the bullet list below.

- Three main components of I4.0: IoT, CPS, and SF
- Three main features of I4.0: Horizontal Integration, Vertical Integration, and End-to-End Digital Integration of Engineering
- The central paradigm of I4.0 is: Augmented Operator, Smart Machine (SM), and SP.

Furthermore, this glossary considers other terms that this thesis author has personally experienced misunderstanding of meanings. For instance, the need for distinguishing between CPS and CPPS comes from the merging of their meaning also by experts in the field. With regards to the second point, this glossary must be further thought as an attempt to address the common ‘lost in translation’ when talking about I4.0 elements and principles. Hence, next sections 2.2.1 is devoted to stressing the most recurrent miscommunications, and to providing the differences and similarities among I4.0 elements.

Finally, this glossary list disregards widely accepted terms beyond the same I4.0, e.g. ‘Internet’, ‘Machine Learning’, or ‘Artificial Intelligence’. The same applies to terms and issues especially belonging to fields different from Industrial and Manufacturing Engineering (IME), and Operation Management (OM), since this dissertation aims at these research fields. For instance, the glossary does not include terms as ‘blockchain’, and it does not address an ontology of I4.0 security.

The list of this glossary is provided in alphabetical order.

Augmented Operator – The term augmented operator refers to the centrality of the human operator within the I4.0 vision. This centrality relies on fact that humans are the most flexible entity in the production system, since they can deal with a wide range of different jobs, from routine to conceptual tasks, by leveraging technological support (Weyer et al., 2015).

Asset – As defined in the 'Reference Architecture Model Industrie 4.0' (RAMI 4.0) by BITCOM, VDMA and ZWEI, assets are all the physical components that have a value for an organization, namely manufacturing parts, documents, ideas, dashboards up to human being (Hankel & Rexroth, 2015). In a nutshell, all existing objects, and people. The entity[33] is the alter ego in the information world – also named 'cyber world' and 'digital world', and the communication of these two worlds for the connection between assets and entities is made through the 'integration' (Hankel & Rexroth, 2015).

Big Data (BD) – The expression BD has over time moved from datasets characteristics in relation to the current technologies, to the technologies designed in order to economically extract value from very large volumes of a wide variety of data, by enabling the high-velocity capture and analysis (Gantz & Reinsel, 2011). BD main description is possible through the '5 Vs' characterization, which extends the '3 Vs' - i.e. 'Volume', 'Velocity', and 'Variety', adding the 'Value', and the 'Veracity' (Demchenko, Grosso, De Laat, & Membrey, 2013). The means of each 'V' is reported according to J. Li, Tao, Cheng, and Zhao (2015): volume refers to the large amount of data; variety refers to the great number of types of data, mostly of very different nature; velocity refers to the high speed of data processing; variability refers to the value of each datum more variable than traditional datasets; value refers to 'the low density and the high overall value of BD'.

Big Data Analytics (BDA) – BDA are techniques to extract value from challenging amounts of data (Aceto et al., 2019). BDA eventually support the I4.0 system by overcoming the emergence of cheap sensors and data storage, very often cloud-based, that increases the data availability, i.e. the BD at last, however in the form of raw data rather than of structured data (Thoben et al., 2017).

Cloud Computing – Cloud Computing is a model that enables ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources, namely networks, servers, storage, applications, and services (Mell & Grance, 2009). It has the advantages of (i) leaving the management of service to an expert-provider, and (ii) working in real-time (Mell & Grance, 2009). It is sometimes modified in Fog Computing or also named simply Cloud (Aceto et al., 2019), and in the following I stick to this use. Cloud provides unlimited computing resources and storage capacity (Xiufeng Liu, Thomsen, & Pedersen, 2013), then it is highly scalable.

Cloud Manufacturing – Cloud Manufacturing moves from Cloud, leveraging its same service-oriented architecture (Yongkui Liu & Xu, 2017). According to Thames and Schaefer (2016), Cloud Manufacturing refers to on-demand access to a shared collection of distributed manufacturing resources via network. The goal of Cloud Manufacturing is to form production systems that are flexible, adaptive, intelligent, and Mass Customization oriented (Thames & Schaefer, 2016).

Cyber-Physical System (CPS) – It is the integrations of computation and physical processes. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computation and vice versa (E. A. Lee, 2008). CPSs lie on the '5C architecture' (J. Lee, Bagheri, & Kao, 2015). The '5C architecture' is used in chapter 3, here it is just mentioned that it extends the former '3C architecture' – i.e. computation, communication and control – to tailor the CPS for smart factories (Ahmadi, Sodhro, Cherifi, Cheutet, & Ouzrout, 2018). Furthermore, next sub-section 2.2.1 provides a brief discussion on difference between CPS and (DT).

Cyber-Physical Production System (CPPS) – CPPSs consist of autonomous and cooperative elements and subsystems that are getting into connection with each other across all levels of production with

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[33] Source: DIN SPEC 91345:2016-04.

regards to specific situations, i.e. machines up, production operations, and logistics networks (Monostori, 2014). In section 2.2.1 the difference between CPS and CPPS is provided to solve the misunderstanding in the research community previously introduced.

Digitalization – Brennen and Kreiss (2016) have analyzed the difference between the terms digitalization and digitization, very often used equivalently. In the authors' definition, 'digitization' is the physical process of converting analogue streams of information into digital bits, and 'digitalization' is "*the process restructuring many domains of social life through digital communication and media infrastructures*". Especially with regards to the industry, 'digitalization' refers to the use of digital technologies and digitized information to create company value in new ways and to benefit from them (Gobble, 2018). Bloomberg (2018) further introduces the concept of digital transformation as disruptive business changes in terms of business models and strategies.

Enabling Technologies – Industry 4.0 is marked by highly developed *automation* and digitalization processes and by the use of electronics and information technologies (IT) in manufacturing and services (Obitko & Jirkovský, 2015; Roblek et al., 2016). Some of the scientific literature has focused on component suites, mostly technology-based, enabling the I4.0 (Oztemel & Gursev, 2020). The reason is the importance for the companies to primarily understand the potential transformation from machine dominant manufacturing to digital manufacturing, due to the features and content of the same I4.0. However, the identification of enablers lies on the challenges that each research wants to face, and for this reason sometimes are selected technology paradigms (e.g. Cloud), sometimes enablers are research fields (e.g. Artificial Intelligence and BD), other times they actually are technologies (e.g. Internet), or specific adoption of technologies (e.g. IoT) (Aceto et al., 2019). Furthermore, the identification of the enablers relates to the scientific field in which the research is performed, as stated by Aceto et al. (2019) who performed an analysis of I4.0 enablers in ICT. Probably, the most disseminated enablers are the nine technology trends proposed by Rüßmann et al. (2015). There is a huge amount of literature discussing how to enable I4.0 in manufacturing. Sometimes authors refer to them as 'methods and technologies' (Moeuf et al., 2018), sometimes as just 'technologies' (Liao et al., 2017; L. Da Xu et al., 2018). There are also different approaches, as the one by Xiulong Liu, Cao, Yang, and Jiang (2018), who performed an analysis of technologies (still mainly ICT-based) useful to a specific manufacturing environment, i.e. warehouses. However based the identification of I4.0 enablers, they are always compliant with the I4.0 main component, features, and central paradigm, and it is possible to state that all the enabling models lie on a BD and IoT common base (Aceto et al., 2019).

End-to-End engineering – It encompasses both the manufacturing processes and the manufactured product, achieving seamless convergence of the digital and physical worlds, and it systematically analyses the data obtained throughout the production process, focusing on quality and customer satisfaction. It allows quick decisions, with the follow-up to furnished products and (Brettel, Klein, & Friederichsen, 2016; Jung, Morris, Lyons, Leong, & Cho, 2015; J. Lee et al., 2014). It is also known as End-to-End (Digital) Integration (Kagermann et al., 2013).

Horizontal Integration – This considers all the links among business partners within the value chain, establishing and maintaining networks that create and add value as a real industry value chain (W. Bauer, Hämmerle, Schlund, & Vocke, 2015; Rennung, Luminosu, & Draghici, 2016; Günther Schuh, Potente, Wesch-Potente, Weber, & Prote, 2014).

Human-Computer Interaction – Interaction between humans and machines needs to be changeable, namely it needs to avoid situation where machines work without input from operators or vice-versa

(Fasth, Stahre, & Dencker, 2008). This is also true in interaction between humans and computers, which is a subset of the collaboration between humans and machines (see also Human-Machine Collaboration definition). Generally, in the interaction with a computer, the human input is the data output by the computer and vice-versa. The aim of this collaboration is to decrease the operators' mental workload (i.e. cognitive tasks) and improve their performances in operations, by means of an increased level of cognitive automation together with an improved management of information flows, that eventually enhances manufacturing flexibility (Choe, Tew, & Tong, 2015).

Human-Machine Collaboration – Although the Human-Machine Collaboration is not really stressed in the I4.0 literature, I believe its definition is useful to address the apparent dichotomy between Augmented Operator and Human-Computer Interaction, as it is described in sections 2.1 and 2.2. The Human-Machine Collaboration varies between 'Human-Robot Interaction' and 'Human-Machine Interface' (Gualtieri et al., 2018). The former belongs to the specific 'Cobot' field, as it refers to the direct interaction between robot and human operator (Peshkin et al., 2001). The latter refers to the use of DT to recreate physical-mathematical models of tangible objects, useful to draw insights of their behavior, otherwise undisclosed, by means of tools such as simulation, and Virtual and Augmented Reality (Gualtieri et al., 2018).

Industrie 4.0 – It is the high-tech strategy of the German government aimed at securing the German manufacturing leadership worldwide (K. Zhou, Liu, & Zhou, 2015). Similar initiatives, beyond the already cited 'Factory of the Future' of the European Commission, are chronologically listed in Table 2.1.

Industry 4.0 – The expanded, technical, definition of 'Industry 4.0' in this dissertation sticks to the study by Lasi et al. (2014). The term, lent by the software versioning, identifies a new fundamental paradigm shift in industrial production, satisfying visions of future production systems characterized by modularity and efficiency.

Industrial Internet of Things (IIoT) – IIoT, also 'Industrial IoT', is the specific application of IoT to the vision of I4.0[34]. It can be summarized as sensor-equipped industrial machines, computers, and people connected by not only Internet technologies, but also the Internet itself, which works as a global communication infrastructure enabling intelligent industrial operations, using advanced data analytics for transformational business outcomes (Aceto et al., 2019).

Internet of Things (IoT) – The first appearance of the term 'Internet of Things' is tracked at the turn of the 2000s in the works on auto-identification and networked infrastructures especially in logistics (Weyrich & Ebert, 2015). The IoT is a concept in which the virtual world of information technology integrates seamlessly with the real world of things, that becomes more accessible through computers and networked devices regardless the users' typology (Uckelmann, Harrison, & Michahelles, 2011a). A deeper discussion on IoT in industry is proposed in next chapter, and some insights to its meaning towards I4.0 is in this chapter presented in section 2.2.1.

Mass Customization – Manufacturing Mass Customization is a production strategy that focuses on the pushed production of personalized products, through (i) flexible processes, (ii) modularized product design, and (iii) integration among supply chain members along the value chain (S. M. Davis, 1989). Especially in recent years, the development of web-based tools allowed to solve the fundamental principle of Mass Customization, i.e. the co-existence of scale production effect and customized products,

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[34] Source: Business guide to Industrial IoT (industrial Internet of Things). Available at link: https://www.i-scoop.eu/internet-of-things-guide/industrial-internet-things-iiot-saving-costs-innovation/. Last access: 2020.01.30.

triggering an even increasing interest to IME, and OM. In I4.0 products are produced in individual batches nonetheless maintaining the economic conditions of mass production (Lasi et al., 2014).

Table 2.1 - Chronological list of I4.0 initiatives worldwide

Initiative	**Country**	**Issue**	**Source**	**Web link for consultation**
Industria Connectada 4.0	Spain	2014	Gobierno de Espana, Ministerio de Economıa, Industria, y Competivitad: Industria Conectada 4.0	http://www.industriaconectada40.gob.es/Paginas/index.aspx Last access: 2020.01.24
Future Of Manufacturing	UK	2014	Future of Manufacturing	https://www.gov.uk/government/collections/future-of-manufacturing Last access: 2020.01.24
Manufacturing Innovation Strategy 3.0[35]	South Korea	2014	Wiktorsson, Noh, Bellgran, and Hanson (2018)	
Made in China 2025	China	2015	Wübbeke and Conrad (2015)	
Make in India	India	2015	Trotta and Garengo (2018)	
Society 5.0	Japan	2016	Declaration to be the world's most advanced IT nation 2016	http://japan.kantei.go.jp/policy/it/2016/20160520full.pdf Last access: 2020.01.24
Smart Industry	Sweden	2016	Smart industry	http://www.government.se/498615/contentassets Last access: 2020.01.24
Piano Industria 4.0	Italy	2016	Piano nazionale Industria 4.0	http://www.sviluppoeconomico.gov.it/index.php/it/industria40 Last access: 2020.01.24
Made Different	Belgium	2016	Made Different, Enabling the Industry of the Future	http://www.madedifferent.be/en Last access: 2020.01.24
Smart Industry	Netherlands	2017	Smart Industry	https://www.smartindustry.nl/ Last access: 2020.01.24
Manufacturing Usa[36]	USA	2017	Manufacturing USA	https://www.manufacturingusa.com/ Last access: 2020.01.24
Industrie du Futur[37]	France	2017	Industrie du Futur	http://www.economie.gouv.fr/nouvelle-france-industrielle/industrie-du-futur Last access: 2020.01.24
Industria 4.0	Portugal	2017	Republica Portuguesa, Ministro da economia, Industria 4.0	

(Near) Real Time – The aim of the 'real-time' is to provide the business intelligence (BI) with zero-latency information coming from analytics of BD (Xiufeng Liu, Iftikhar, & Xie, 2014). It lies on two stages. The former is the data integration, which runs at a regular time interval (e.g. daily, weekly, or monthly). The latter is the real-time analytics, which is performed after the integration process to get the insights of data with the help of analytics tools (Xiufeng Liu et al., 2014). Real Time has also developed into near-real time, a declination of the real time information request that means "to return analytics within a time limit", otherwise information loses its value (Xiufeng Liu et al., 2014). Beyond the BDA potentiality, the real-time requirements also comes from Cloud potentiality (Aceto et al., 2019).

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[35] Also known as Smart Factory.

[36] It follows the "Advanced Manufacturing Partnership" program of 2011 (J. Zhou et al., 2018).

[37] It follows the "Nouvelle France Industrielle" program of 2011 (J. Zhou et al., 2018).

Servitization – Servitization is the concept of emphasizing the customers' focus to products and services, by combining support to and knowledge from purchasers and clients (Vandermerwe & Rada, 1988). In the digitalization era, the further stressed focus on customers' desires has led to the 'Digital Servitization', namely the supply of digital services encapsulated within physical products (Vendrell-Herrero et al., 2017). Furthermore, as it became of interest to manufacturing, Roy et al. (2009) defines manufacturing servitization as innovation of organizational capabilities and processes, from product sales to integrated product services that deliver value in use.

Smartification (of something) – The term 'Smart' in the I4.0 context, refers to the fusion between Operational Technologies (OTs) and Information and Communication Technologies (ICTs), as a benchmark for depicting how industry is taking a path from previous positions (Aceto et al., 2019). OTs are hardware and software that detect or cause changes in physical processes through the direct monitoring and/or control of industrial equipment, assets, processes, and events[38]. On the other hand, ICT is and extension for Information Technology (IT) that stresses the role of unified communications and the integration of telecommunications and computers, as well as necessary enterprise software, middleware, storage, and audiovisual systems, that enable users to access, store, transmit, and manipulate information[39] [40]. In general, ICTs do not include embedded technologies that do not generate data for enterprise use[41].

Smart Factory (SF) – The definition of 'Smart Factory' could be officially attributed to Lucke et al. (2008). The following explains why. The concept of 'smart' in industry has different precedents. For instance, Babb in 1992 discussed the concept with regards to intensive system integration by means of both hardware and software. Even early, Elliott and Hyduk in 1989 proposed the term 'smart' to identify factory in which the manufacturing islands are connected by means of electronic components. Another concept useful for developing the 'smart factory' idea as it nowadays is, comes from Teresko in 2004. In his work the need for standards regulating the interchanbgeability of machines claimed the manufacturing community attention. However, several studies link the concept of 'smart factory' to the work of Lucke et al. (2008). Among these studies, special mentions deserve contribution from Hermann et al. (2016), Kang et al. (2016), and Lasi et al. (2014), outstanding because of the number of citations they received on Scopus (i.e. more than 500 the first work, and about 300 and 700 respectively the second and third work). The following explanation of SF is then rearranged from the study of Lucke et al. (2008). SF is a factory characterized by (i) hardware with the ability to communicate and interact with its environment (i.e. the 'calm-systems'), and (ii) the ability to take into consideration context information (i.e. the 'context-aware application'). The context-aware module assists people and machines in execution of their tasks based on three core elements: (i) 'identification', i.e. assignment of information from the virtual world to real world objects; (ii) 'localization', i.e. the positioning phase on a large scale; and (iii) 'status knowledge', for the context-aware information.

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[38] Source: Gartner Glossary. Available at link: https://www.gartner.com/en/information-technology/glossary/it-information-technology. Last access: 2020.01.27.

[39] Murray, J. (2011). Cloud network architecture and ICT. Online, available at link: https://itknowledgeexchange.techtarget.com/. Note that just the link visualisation has been modified for the sake of the footnote layout, nevertheless the URL actually works indeed. Last access: 2020.01.27.

[40] Information and Communication Technology. Online, available at link: https://web.archive.org/web/20130917072505/. Note that just the link visualisation has been modified for the sake of the footnote layout, nevertheless the URL actually works indeed. Last access: 2020.01.27

[41] Source: Gartner Glossary. Available at link: https://www.gartner.com/en/information-technology/glossary/it-information-technology. Last access: 2020.01.27.

Smart Product (SP) – SPs are products able (i) to require production resources and orchestrate their production process, (ii) communicate their presence, characteristics, and requirements to the surrounding machines or humans, and especially (iii) they are continuous source of data about themselves, the environment they are immersed in, and the interaction with the user (Porter & Heppelmann, 2014; Weyer et al., 2015).

Smart Machine (SM) – SMs are machines able to self-organize to meet the production requirements on the basis of communication with SPs and production environment (Weyer et al., 2015).

Smart Manufacturing (SMfg) – Although the term 'Smart Manufacturing' is strictly related to the Anglo-Saxon lexicon, especially the US one as alternative to 'Industry 4.0' (Thoben et al., 2017), its definition form Wallace and Riddick (2013) of 'intensive application of IT at the shop floor level and above to produce data useful to enable intelligent, efficient, and responsive operations' is worldwide recognized, and further extended to the whole supply network. The aim is then to provide infrastructures suitable to comply with the recent manufacturing evolution responding to new industrial scenario solution, i.e. towards agile innovation, and energy and environmental sustainability (J. Davis et al., 2015).

Vertical integration – It aims to make factory products and production processes intelligent, e.g. with regards to inventory levels and preventive maintenance. Making factories intelligent happens by means of communication among assets within the corporation, both physical (e.g. machines) and informational (e.g. ERP), in order to form a self-organized system flexible and reconfigurable (S. Wang et al., 2016).

2.2.1 *Insights to I4.0 perception and system design*

In the following, differences of meanings and relationship among some components are addressed.

Augmented Operator – Human Computer Interaction – Human Machine Collaboration

The concept of Augmented Operator sounds to be opposing to the concept of Human-Computer Interaction, since the former lies on the human flexibility, and the latter seems to narrow the operators' area of competence to just physical tasks. This issue is solved by the Human-Machine Collaboration component previously named 'Human-Machine Interface', since this element sets forth that humans make decisions based on data processing (i.e. the cognitive tasks). In fact, 'Human-Machine Interface' highlights that the Human-Computer Interaction, which eventually is its subset, is not concerned with relegating operators to just physical activities, rather than it is concerned with assigning calculation to computers (or more in general to machines) and providing users with powerful information from data analytics for efficient decision-making performances (Aceto et al., 2019).

Big Data and Big Data Analytics

There is a very common misunderstanding of means between BD and BDA. It could emerge, for instance, from the same definitions provided by Gantz and Reinsel (2011) and (Aceto et al., 2019) with regards to BD and BDA respectively, mentioned above in the glossary list. The supposed overlap disappears just considering the difference between the word 'technologies' and 'techniques', used in the definition of BD and BDA respectively. In fact, the term 'technology' relates to "advanced scientific knowledge used for practical purposes"[42] and it entails the use of machines and equipment. Whereas the term 'technique' relates to "methods of doing something"[43] by means of skills, ability, and tools.

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[42] Source: https://www.macmillandictionary.com/dictionary/british/technology. Last access: 2020.02.05.

[43] Source: https://www.macmillandictionary.com/dictionary/british/technique. Last access: 2020.02.05.

Therefore, BDA can be considered a subset of the BD. The mere linguistic argument above, is translated in the requirement 'Value' for the BD. In fact, as also stated by S. Wang et al. (2016), among the large quantity of data captured (i.e. the BD) just a small part of data is suitable to be evaluated through data analytics methods (i.e. the BDA), and therefore this 'V' is the key to unlock BDA as tools suitable for the BD contents. I believe this remark useful since the research community still confuse BD and BDA, for instance when discussing the I4.0 enabling technologies. In the following some examples. S. Wang et al. (2016) considers the 'Big Data', while L. Da Xu et al. (2018) talk about 'Big Data Analytics'. Furthermore, both 'Big Data and (its) Analytics' are mainly considered together, as in Moeuf et al. (2018), Rüßmann et al. (2015), and Saucedo-Martínez, Pérez-Lara, Marmolejo-Saucedo, Salais-Fierro, and Vasant (2018). It is my opinion that the most suitable way to deal with the issue is to consider 'Big Data Analytics' as key component, and 'Big Data' as the real technological enabler, as in Aceto et al. (2019).

Cloud – Cloud Manufacturing and other Intelligent Manufacturing Systems

Due to its scalability, Cloud (i) does not require a careful dimensioning and forecast of needed resources, and (ii) and the provision of the related service is adaptive to the changing factory structure and costs (Armbrust et al., 2010). These characteristics eventually pave the way for the concept of Everything-as-a-Service (XaaS) (Armbrust et al., 2010). In this sense, the suitability of Cloud Computing to the I4.0 keeps pace with the wireless network suitability that also lies on the same scalability (S. Wang et al., 2016), and it is a basis for the Cloud Manufacturing paradigm (Yongkui Liu & Xu, 2017).

A first difference between Cloud and Cloud Manufacturing is that in the latter humans are key participants to the process, while in Cloud Computing humans are ideally kept out of the operations at all (Hao & Helo, 2017). A second, main difference is that Cloud Manufacturing concept of service does not refer to just a service provision (Aceto et al., 2019) and propose to develop a kind of manufacturing community (L. Zhang et al., 2014). In fact, although belonging to the IMS models, IMSs adopt Cloud in IT and towards new business models, whereas Cloud Manufacturing makes use of Cloud services to fully provide distributed resources that are managed in centralized way (X. Xu, 2012). In this sense Cloud Manufacturing leverages Cloud paradigm at variance with other IMSs that use Cloud Computing as a technology trend (Rüßmann et al., 2015), namely IMSs such as 'Smart Manufacturing' and 'Industry 4.0' use the Cloud to support plant activities and operations, or to build a real data-driven industry value chain, respectively (Thoben et al., 2017).

CPS and DT

CPSs are thought to allow intensively interaction between the 'cyber space' and the 'physical processes' (Hu, Xie, Kuang, & Zhao, 2012; Yang Liu, Peng, Wang, Yao, & Liu, 2017), and in this sense, CPS concept is similar to DT. In fact, DT refers to a comprehensive physical and functional description of components, products, or systems. DT includes more or less all information which could be useful to all lifecycle phases, nevertheless the time of access to the same information (Boschert & Rosen, 2016). As a matter of fact, CPSs and DT share the same essential concepts of an intensive cyber–physical connection, real-time interaction, organization integration, and deep collaboration, and they both are used to describe cyber–physical integration (Tao et al., 2019). However, CPS and DT are different from many perspectives, as shown by the work of Tao et al. (2019) who analyzed different works on CPS and DT to highlights the main differences. Firstly, as CPSs were derived from extensive applications of embedded systems, they belong more to a scientific category requiring collaboration of different disciplines, rather than being an engineering specialization as the DT is. These disciplines are mechanical and electrical engineering, and computer science, as stated by Thoben et al. (2017). Secondly, they both include the physical and the cyber/digital part. However, CPS is the integration of computational and physical processes by means of sensors and actuators (La & Kim, 2010), aiming to add new capabilities to physical systems by means of communication and control processes (L. Wang et al., 2015). On the other hand, DT is the use of a digital copy of a physical systems by means of models and data, in order to provide a comprehensive physical and functional description of a component, product, or system with the aim of performing real-time optimization (Söderberg et al., 2017). To conclude, Tao et al. (2019) state that DT might be eventually considered a "*necessary foundation for building CPS and for opening the way to the realization of CPS*".

CPS and CPPS

Since CPS refers to the connections between physical devices and the cyber world (J. Lee, Bagheri, et al., 2015), it is clear that CPPSs are systems other than CPSs (Muhuri et al., 2019). Being more clear, CPPS is a platform aimed to build a network environment for using CPS technologies (K. Zhou et al., 2015), and in this sense they are more related to the IoT concept rather than to the CPS one (Bruner, 2013), as already stated in the introduction paragraph to the glossary list. Furthermore, sometimes there is confusion between CPPSs and the same IMSs: for instance Schlechtendahl, Keinert, Kretschmer, Lechler, and Verl (2015) mean CPPS when they talk about I4.0, whereas Kagermann et al. (2013) clearly refers to CPPS as I40 enabler. In favor of the second stance, Monostori (2014) discusses the CPPS as a step in development of a manufacturing system, rather than a manufacturing system itself.

IoT, IIoT, and other enablers for IMSs

From the definitions provided in the glossary above, IIoT clearly differs from IoT as it is its subcomponent, but the difference with other IMS components seems to be fuzzy. To disclose the real difference among these terms, Jeschke, Brecher, Meisen, Özdemir, and Eschert (2017) state that IIoT is strictly related to technology stack, that is to say IIoT leads to the I4.0 as its component focused on manufacturing processes. In a nutshell, IIoT is the industrial subset of IoT and is a very specific component of I4.0 application to Industry. Finally, IIoT is similar but however slightly different to other IMS enablers, such as CPPS (as stated above) and Industrial Internet. Especially the last one is better to be understood as a framework focused on unification of industrial machines and software (Bruner, 2013), rather than as IIoT synonym as sometimes proposed[44].

2.3 I4.0 framework as its functional view

The following framework adopts hybrid mapping using rules from IDEF0 and black box modelling for providing a functional view of I4.0. IDEF0 was derived from a well-known graphical language, i.e. the structured analysis and design technique (SADT) (Ross, 1977; Ross & Schoman, 1977). In this thesis, the graphical notation is adopted according to Lightsey (2001). Black box modelling, useful since OUTPUT replies to the INPUT regardless of the specificity of internal components of the system described, follows drawing rules of Böhm and Jacopini (1966). The modelling further leverages the concept of 'control volume' of black box modelling, as used for solving flow thermodynamics problems[45].

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[44] Source: Industrial internet insights: bring together brilliant machines, advanced analytics and people at work. Retrieved in (Jeschke et al., 2017) at link: https://www.ge.com/digital/industrial-internet.

[45] For more details, visit https://www.me.psu.edu/cimbala/Learning/Fluid/Control_Volume/home.htm. Last access: 2020.08.25

The framework is aimed at providing a simplified I4.0 functional view. Thus, only I4.0 elements belonging to the overall changes addressed by the r/evolution are considered for modelling the framework. These are elements discussed in section 2.1. The simplified functional view of I4.0 is provided in Figure 2.2.

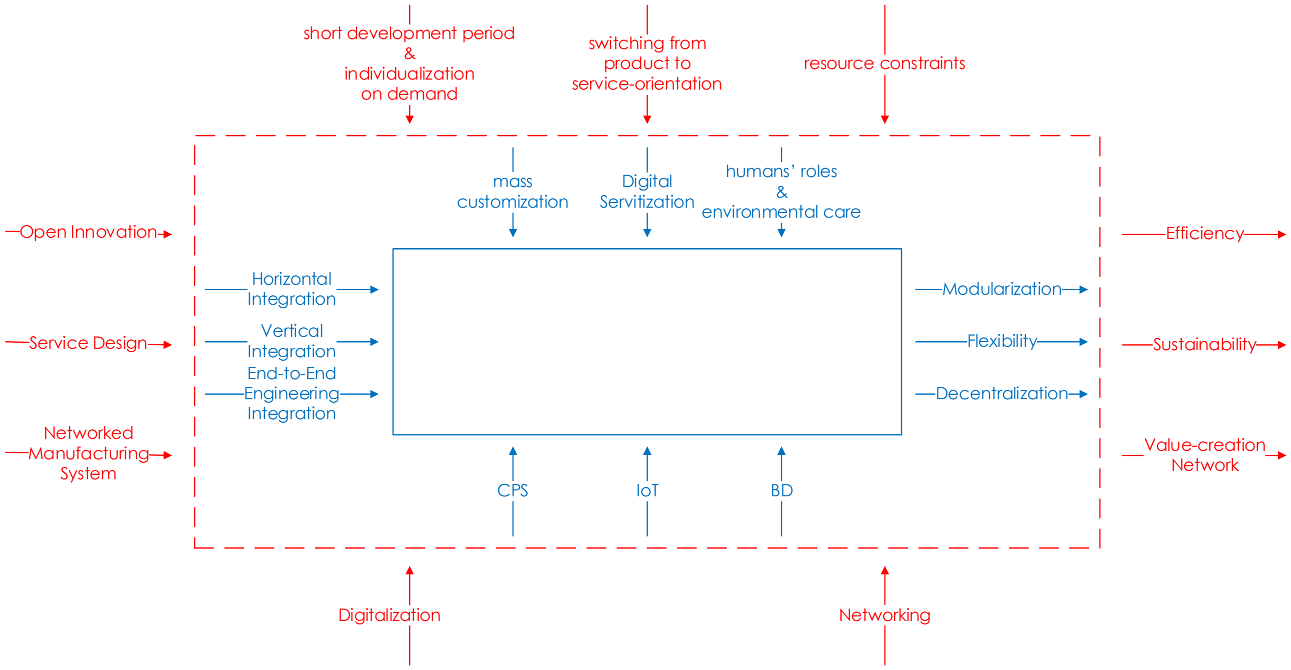

Figure 2.2. Functional view of I4.0

I4.0 and SF systems are represented by black boxes, namely it does not interest to this level of abstraction how the systems work and what is the business. In such a view, I4.0 and SF as its component are bounded by two different control volumes (red line for the I4.0 volume control and blue line for the SF one). External control volume is dashed according to original drawing rules. Arrows represents the elements characterizing the r/evolution. The position at which the arrow attaches to a box conveys the specific role of the interface. Concerning arrow positions, an IDEF0-like drawing rule is adopted. The controls-constraints enter the top of the box. The inputs enter the box from the left. The outputs leave the right-hand side of the box. Resources supporting means for performing the system r/evolution join the bottom of the box.

Socio-economic changes are control parameters of I4.0 driving principle and technology adoptions. These changes are even more shrinking the development period for new products and services due to worldwide market and technology push. Also, the traditional supply of product is no longer enough to the market, which is even more asking the provisioning of services as an add-on of same products, sometimes to the extent that the service becomes for companies the core business or a main source of rewards. Finally, the ever-increasing attention to resources consumption and valorization asks for new way of their utilization. In the SF, these parameters lead to manufacturing principles as mass-customization, digital servitization, and changing of perspective in human role and identity in manufacturing as well as manufacturing sustainability.

To cope with these challenges, I4.0 leverages digitalization and networking. These are resources of the external volume control. From the SF view, these resources turn into ultimate technologies enabling I4.0, i.e. CPS, IoT, and BD.

Concepts acting as input to I4.0-based systems relates to BM principles towards which industry needs to move to accomplish socio-economic change. Namely open innovation, networking of manufacturing systems, and service design. In the SF boundaries, these principles turn into the total integration, thus horizontal, vertical, and engineering integrations, for chasing flexibility, modularization, and decentralization that realize the I4.0 view of industry, pursuing manufacturing efficiency and sustainability, and value-creation network.

2.4 Conclusions

The revolutionary scenario addressed by I4.0, the first in manufacturing industry established ex-ante for a planned 4th industrial revolution, is characterized by both socio-economic and political changes. The characteristics of this r/evolution have been provided, according to the study of Lasi et al. (2014). Drivers of I4.0 changes are shorter product lifecycle, mass customization, resource efficiency, and focus on servitization, which in industrial environment practically translate into new requirements, namely (i) product mass customization, (ii) digital servitization, and (iii) focus on sustainability of business practices. For copying with this new scenario, manufacturing systems, namely the SF, need to push on total integration of systems involved in the SC towards its r/evolution into an efficient VN. In this view of the I4.0, systems r/evolves into digitalized and networked systems leveraging three technologies, namely CPS, IoT, and BD, that realize the SF of I4.0 and achieve expected results of (i) decentralization, (ii) modularization, and (iii) flexibility. It has been showed as these three technologies allow increasing mechanization and automation of systems, as well as their smartification that are directions at which business need to aim for realizing the r/evolution (Kagermann, Helbig, Hellinger, & Wahlster, 2013; Roblek, Meško, & Krapež, 2016).

The analysis carried out has been used for defining a high-level representation of I4.0 and SF systems neglecting some specific components. The reason lies in the fact that the proposed framework aims to only define relation among I4.0 and SF basic concepts, hence in the form of a functional view. The aim is of providing a simple and clear view of I4.0 which is considered, in this thesis, useful for supporting I4.0 dissemination also in environments which traditionally have difficult to cope with novelties. However, definitions of main recurrent terms of I4.0 vocabulary have been provided for fully explaining the vision of I4.0 of this thesis, and for fixing the meanings of terms that will be used in the rest of the thesis.

Results achieved in this chapter, in fact, are the basis of further contributions of this thesis. Specifically, the technology stack here identified to be necessary for implementing SF of I4.0, i.e. CPS, IoT, and BD, will be used for defining a technical reference model of I4.0 in chapter 3. Moreover, the technology approach towards digitalization and networking of systems, will be used in chapter 4 for characterizing the mandatory evolution of industrial systems towards new business requirements of I4.0, by means of a maturity model capable of assessing how far systems are ready for the I4.0 r/evolution, and what potentiality of growing they have.

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3 A Reference Model for I4.0 dissemination in SME industries

In the previous chapter, the technology stack necessary for implementing SF of I4.0, i.e. CPS, IoT, and BD, has been identified. The simplification of the list of technologies realizing SFs of I4.0 has been evaluated useful for this thesis since the will to disseminate I4.0 in environments in which traditionally players strive to understand novelties and their usefulness. In fact, discussing separately the many technologies involved, the industrial environments risk (i) to oversee issues and limitations of the r/evolution, hence missing the opportunity of new applications, as well as (ii) to reinvent the wheel for standards and solutions that are spreading but are not new in industry (Aceto et al., 2019). It remains to be seen how these components operate and are interconnected with each other, to put implementation of such systems into practice.

However, relations among these components of SF still need to be discussed.

For practically developing I4.0 applications, reference architectures (RAs) as well as Reference Models (RMs) must be designed, with the aim of (i) fixing the common standards required by I4.0 for the collaborative organization-partnerships in the VNs, and (ii) providing a guiding blueprint which declare all components needed allowing to structure systems in a suitable manner (Kagermann et al., 2013). RAs belong to the system architecting discipline (Unverdorben, Böhm, & Lüder, 2019). System architecting is designed for realizing 'systems', which in the discipline is defines as in Dickerson and Mavris (2016) 'a combination of connected and interacting elements, which are organized in a certain "*way to achieve a stated purpose and which are separated from their environment by a system boundary*". Elements of the system are separated from other systems and environment, but they can be however linked due to common inputs and outputs. System Architectures address how system components must be organized, the relations existing among same components, and with the environment, and the principles guiding its design and evolution independently of any specific environment and its characteristics in which they are applied (Dickerson & Mavris, 2016; Unverdorben et al., 2019). Different typologies of system architectures exist. Differences relates to the granularity level of details of the architecture designs, listed in the bullet point below from the less detailed to the most detailed, and then represented in Figure 3.1:

- 'Reference Model' (MacKenzie et al., 2006): a RM consists of a minimal set of unifying concepts, axioms and relationships within a particular problem domain, and is independent of specific standards, technologies, implementations, or other concrete details. It is preparatory for designing a RA[46].
- 'Reference Architecture' (Sittón-Candanedo, Alonso, Rodríguez-González, Coria, & De La Prieta, 2019): A RA is a model for an architecture description. It has reference character since it provides a template solution for the architecture for a particular domain. In industrial environment, a RA is a document or set of documents that recommends structures, products, and services to entail in the business arrangement. It refers to industry-accepted best practices, usually suggesting the method or specific technologies to implement.

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[46] Source: DIN SPEC 91345:2016-04

- ‘Architecture’ (Larrinaga et al., 2019): An architecture is a combination of elements of a model based on principles and rules for constructing, refining and using it[1]. An architecture has more components with respect to RA: (i) a feature model broadens RAs key concepts by characterizing their aspects in the architectures, (ii) guidelines discuss how the provided models, views and perspectives are used, finally (iii) reference applications show how different solutions adopted produce different results, and thus illustrate architecture peculiarity and related design decisions.

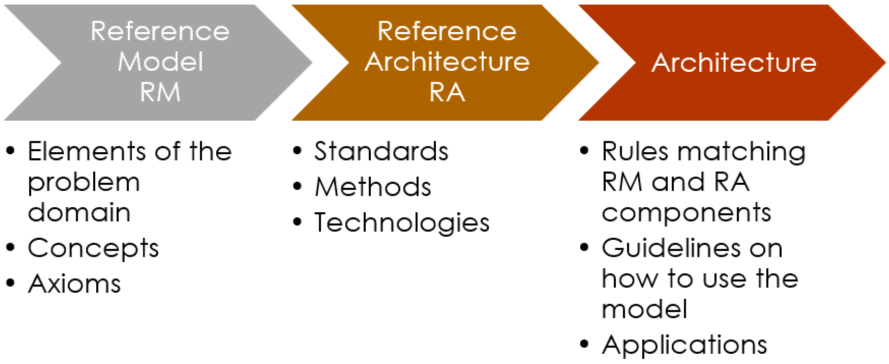

Figure 3.1. Waterfall detailing from RM to an architecture

In the rest of this introduction to the chapter, characteristics of RA relating to its recommendation character are also related to RM. This linguistic license refers to the fact that both represent abstract solution patterns for the design of systems in a specific domain[47]. Hence, the only difference between them is the more practical modelling of RAs, namely a RA develops into a solution pattern configuration of systems provided by RM[48].

In order to provide guidance for all relevant stakeholders involved in the implementation of Industry 4.0 systems, RAs are considered valuable since their capability to meet the requirements below (Unverdorben et al., 2019):

- RAs can be applied for designing I4.0 systems and their specific declination, namely IMSs.
- Ras provide concrete descriptions of ideal-typical I4.0 systems for manufacturing regardless specific production processes.
- RAs describe all relevant functions (i.e. functional architecture).
- RAs describe the relevant logical components (i.e. logical architecture).
- From the RAs blueprint it is possible to derive the customized technical architecture of a system.
- Architectures of ideal-typical systems provided by RAs must be customizable and scalable.

Concerning third and fourth points, different views of RAs are possible to provide, and a same RA can have more views as well as a single view, based on its focus. A view is a representation of one or more aspects of the architecture that provides how the architecture deals with it[49]. It is created and interpreted through its viewpoint that contains information on architecting techniques used (Jiang, Liu, Li, & Shi, 2019). Several viewpoints are usually considered, that allow for definition of architecture content on

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[47] Source: The Open Group. Retrieved from: https://pubs.opengroup.org/architecture/archimate3-doc/toc.html. Last access: 2020.09.16

[48] Source: TOGAF. Retrieved from: https://pubs.opengroup.org/architecture/togaf9-doc/arch/index.html. Last access: 2020.09.16

[49] Source: IASA. Retrieved from: https://itabok.iasaglobal.org/itabok/capability-descriptions/views-and-viewpoints/. Last access: 2020.09.16

different levels of granularity (Unverdorben et al., 2018). The most recursive viewpoints are the functional viewpoint and especially the technical/implementation viewpoint (Ünal, 2019). The former relates to the functional components of the architecture, namely how they support all related activities of the overall system. The latter addresses the technological implementation (Maple, Bradbury, Le, & Ghirardello, 2019).

RAs are considered suitable to provide guidance to implementation of concrete I4.0 systems since their ability to capture fundamentals, functions, and logics of manufacturing environment, and they can be used as a starting point for setting up a concrete system architecture (Mueller et al., 2017). In fact, the possibility of conceptualizing various concepts into coherent layers of abstraction, allows RAs to tune various methods, processes, and technologies that I4.0 has brought into industrial environment (Ma, Hudic, Shaaban, & Plosz, 2017).

Many studies are developed to define a RAs, according to different focus and targets, with the aim of leading I4.0 solutions into existing systems (Drath & Horch, 2014).

Two noteworthy RAs stood out, as generally accepted for structuring new business organizations of I4.0 (Pedone & Mezgár, 2018). In Germany, the working group for Industry 4.0 has developed the Reference Architecture Model for Industry 4.0 (RAMI 4.0), a 3D layered model based on the Smart Grid Architecture Model (Hankel & Rexroth, 2015). The US Industrial Internet Consortium (IIC) has developed the Industrial Internet Reference Architecture (IIRA), consisting of three tiers and four viewpoints (Lin, Miller, et al., 2017), and based on the ISO/IEC/IEEE 42010. While RAMI 4.0 targets mainly industry automation, IIRA aims to bring IoT into a wider target area, including energy, healthcare, and transportation (Lin, Murphy, et al., 2017). However, two models share many similarities (Posada et al., 2015). Since their importance, they are described and compared more in dept in the next section by means of relevant literature available.

Also academia is very involved in designing RAs for I4.0 systems, although one major concern has been aroused: RAs are often stylishly but difficult to put into practice because they either entail too much components, or are too specific of an application (Oesterreich & Teuteberg, 2016). For SMEs is all the more difficult to develop I4.0 systems complying with RAs although suitably designed, because of financial limits to cope with technology stacks suggested (Bordel Sánchez, Alcarria, Martín, & Robles, 2015). Moreover, during the studies carried out towards this dissertation, the author of this thesis has personally experienced that SMEs managers use to think about I4.0 technologies for only benefitting fiscal incentives, more than for developing their I4.0 systems. This mainly is for two reason:

- They figure I4.0 out as something complicated and whose systems are difficult to realize.
- They are unaware of methods and tools as the RAs for better describing and projecting I4.0 systems, since they strive to understand how they work, very often unsuccessfully.

Therefore, they leverage consulting firms, albeit very often without trustworthiness since they are not able to understand the I4.0 basic principles.

In this Chapter a RM for I4.0 principles dissemination within SMEs environment is designed. The aim is of defining few clear-and-valuable principles and technologies to foster the r/evolution of SMEs towards I4.0-compliant systems. The RA proposed wants to be ‘neutral’, namely is designed regardless geography, company dimension, and industry, to further suggest specific model and architecture for successfully implementing I4.0 principles and technologies.

The reminder of the chapter is structured as follows. Section number 1 deals with reviewing two main accepted RAs, i.e. RAMI 4.0 and IIRA. Section number 2 provides a structured literature review on RA designed in systems engineering. Section number 3 defines the methodology adopted for designing the new RM, and then proposes it. Section number 4 validates the model and discusses results. Finally, section number 5 addresses conclusions.

3.1 RAMI 4.0 and IIRA: model description and interoperability

3.1.1 RAMI 4.0

The RAMI 4.0 has been developed for widening I4.0 acceptance and for controlling its repercussion on industrial systems, towards vertical, horizontal, and end-to-end engineering integrations (Pisching, Pessoa, Junqueira, dos Santos Filho, & Miyagi, 2018). Provided by the government-led initiative, Plattform Industrie 4.0, it describes the fundamental aspects of I4.0, and it aims to define standards and use cases of I4.0 (Pisching et al., 2018). The following description sticks to the characterization of Grangel-González et al. (2016) and Zezulka, Marcon, Vesely, and Sajdl (2016).

RAMI 4.0 provides the connection between IT, manufacturing plants, and the product life cycle in a three-dimensional space for approximately fifteen industrial branches. Each dimension, mapped onto an axis of the 3D space, is divided into different layers. As a result, the RAMI 4.0 representation consists in a layered cube.

The vertical axis represents the IT perspectives, where complex systems are decomposed into smaller manageable parts, in the look of (i) market aspects, (ii) functions, information, and communication, and (iii) integration ability of the components. Thus, it comprises layers ranging from the physical device, i.e. asset, to complex functions as they are available in ERP systems, i.e. function. The layers are listed in the bullet list below:

- Asset Layer: it represents the reality. 'Asset' refers to the definition provided in Chapter 2, namely it relates to physical components, parts, documents, representations, ideas and so on.
- Integration Layer: it realizes the connection between physical reality and virtual reality worlds. It provides information on the assets in a suitable format for being processed by computers. Thus, it is composed of both hardware and software, namely it functions as both (i) digitalization system via ICT (e.g. RFID readers, sensors, actuators, and Human-Machine Integration HMI meant as Human-Computer and Human-Machine interaction), and as (ii) systems controls unit.
- Communication Layer: it provides standards for communications (e.g. data format, communication protocols), and also services for controlling the integration layer.
- Information Layer: it establishes rules for preprocessing events and coherently describe them for the higher level. It entails providing data integrity and their integration for obtaining higher quality structured data by means of service interfaces.
- Functional Layer: it enables formal description of functions and creates platform for horizontal integration of various functions. It contains modeling environment for servicing business processes and executing environment for applications and technical functionality. It generates rules and decision-making logics. Although some tasks referred to this layer can be executed in lower layers, those related to remote access and horizontal integration are executed only within this layer because of only this layer assure the needed data integrity.

- Business layer: it secures functions in the value stream by means of regulatory framework conditions, enables mapping processes and business models, addressing rules with which the system must comply, and finally establishes inter-dependences of different business processes.

The horizontal axis on the left-hand side indicates the product life cycle distinguishing between 'Type' and 'Instance', which refers to two phases of (i) devising assets (i.e. design, development, testing products), which is preparatory to the its serial production that leads to the second phase of (ii) installation in a particular system. Production phases is incorporated within the Instance. The RAMI 4.0 model enables the representation of data gathered during the entire life cycle, and its value stream in the totally digitalized production according to IEC 62890 Value Stream standardization. Thus, life cycle is linked to value-adding processes.

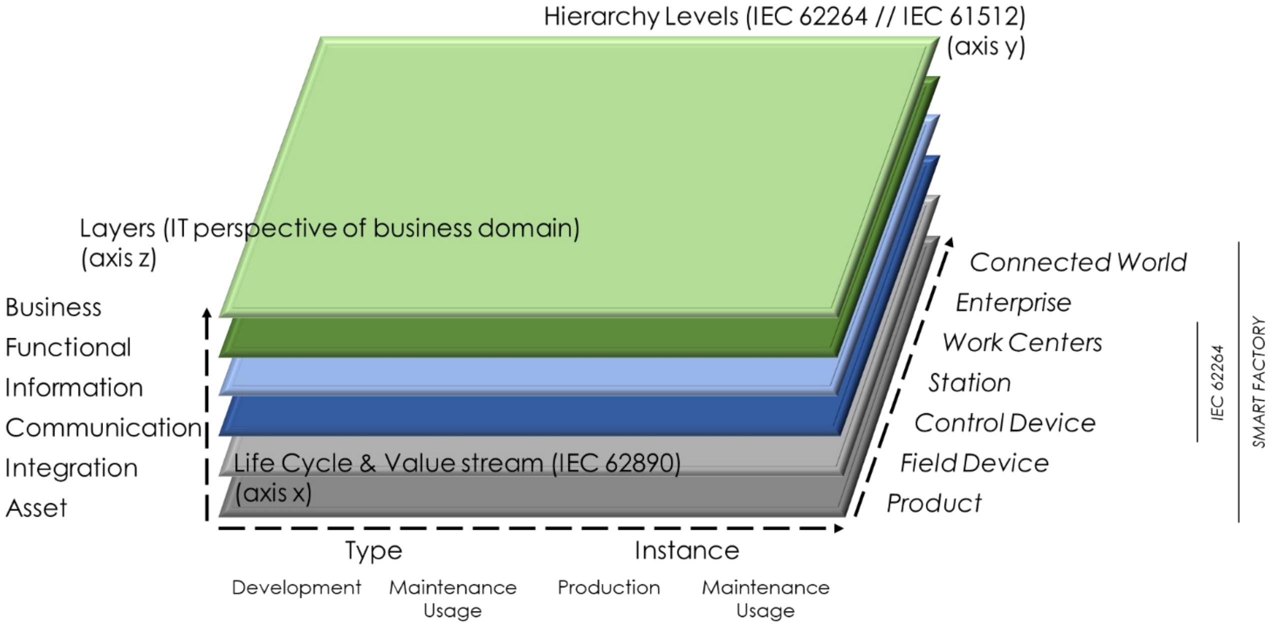
The horizontal axis on the right-hand side organizes the locations of the functionalities and responsibilities in a hierarchy. The model extends the hierarchy levels defined in the standard IEC 62264 for Enterprise-control system integration, and 61512 for Batch Control, towards specification of components in a single unit. Extension consists of adding the concepts 'Product' on the lowest level and 'Connected World' at the top level, for going beyond the boundaries of an individual factory and describing describes business stakeholders.

Beyond the RAMI 4.0 representation, Adolphs et al. (2015) have provided a representation of I4.0 components devoted to assists producers and system integrators to create hardware and software components for the I4.0. The model is a combination of three cyber and physical elements:

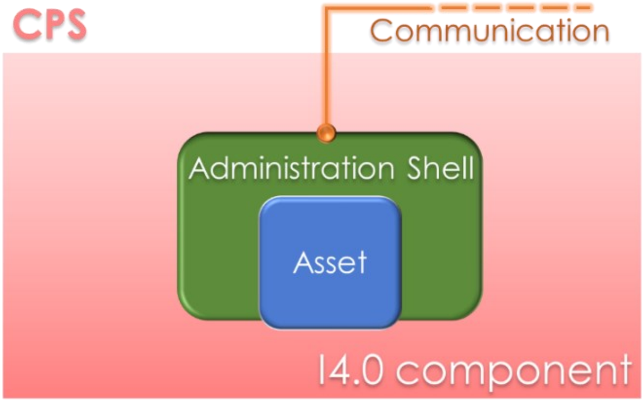
1. Thing: e.g. objects as machines, their components, but also mechanical drawings.
2. Administration Shell: it is the electronic container of secured data during all thing life cycle, suitably made available when necessary. It covers the virtual representation and the technical functionality of things. It provides the component with:
   a. Data Management: i.e. mechanisms to store and manage large amounts of data and information generated by business players, e.g. information related to configuration, maintenance, or connectivity with other devices. Data and information are stored within the 'Manifest' of the virtual representation of things which also contains data about individual life cycle phases of the event
   b. Functions: i.e. operations, maintenance tasks, or complex algorithms implementing business logics, for facilitating the interaction between the I4.0 component and other actors, including human users.
   c. Services: information can be made available to different users and can be accessed in various use cases beyond the boundaries of the component, and of the asset producing it, through enterprise networks or cloud
   d. Integration: in combination with communication protocols, the shell offers the possibility of easy integrating I4.0 components
   e. Modularity: each specific part of an object should be able to store information in the Administration Shell. This ensures availability of and accessibility to all information for follow-up analysis.
3. The Component: it is the joint of Things into their Administration Shell. The most important feature is the communication ability among the virtual entities with real entities.

Joints between Thing and Administration shell are provided by operational technologies such as sensors, actuators, PLC, as well as RFID, embedded system of SM, and more in general, by devices capable of digitalizing assets. Of course, for practical utilization of I4.0 components, common semantic models and transparency to the total integration is needed.

Figure 3.2 provides the RAMI 4.0 structure, and the I4.0 component design, rearranging original artwork of Adolphs et al. (2015) and commented as discussed by (Pisching et al., 2018), and Zezulka, Marcon, Vesely, and Sajdl (2016), who highlighted the realization of the SF and the CPS views of RAMI 4.0 and I4.0 component respectively.



(a)



(b)

Figure 3.2. (a) RAMI 4.0 and (b) I4.0 component rearranging original artwork of Adolphs et al. (2015) and commented as discussed by Pisching, Pessoa, Junqueira, dos Santos Filho, and Miyagi (2018), and Zezulka, Marcon, Vesely, and Sajdl (2016)

3.1.2 IIRA

IIRA is proposed by an industry-led initiative, the Industrial Internet Consortium (IIC), and it is a general purpose reference architecture, business-value driven, focused on definition of standards for open concrete architectures of Industrial Internet Systems, towards interoperability in industry and standardization of technology development (Lin, Miller, et al., 2017). Following description sticks to characterization of IIRA provided by (Pedone & Mezgár, 2018) and (Unverdorben et al., 2018).

IIRA supports large amount of industrial use cases codified by conventions and common practices central of its Internet Information Service. The architecture framework is based on standards by the ISO/IEC/IEEE 42010 (v. 2011). The architecture is composed of 'concerns' (topics of interest to the system), 'stakeholders' (entities involved into the system) and 'viewpoints' (conventions describing and analyzing specific system concerns). Four different viewpoints represent different technological and economic perspectives, and they support identification and classification of architectural concerns of Internet Information Service for methodologically solve them by an iterative approach (Lin, Miller, et al., 2017):

- Business viewpoint: it deals with concerns of the relevant stakeholders, as well as their corporate visions, values, and goals regarding the development of an IIoT system within the considered system. The viewpoint also provides the basic system capabilities that allow to achieve the expected results.
- Usage viewpoint: it refers to the concerns of expected use of the system, and how the system realizes the necessary capabilities identified in the business viewpoint as well. Within the usage viewpoint coordination activities of tasks over different components are described and form the basis for the definition of system requirements.
- Functional viewpoint: addresses the functional components of the IIoT system, and the relative structure that embed them in. Furthermore, arranges the interaction between components both internal and external to the environment of the system. The goal is to support all related activities of the overall system. Functional viewpoint is the most important concerning interoperability since the need for definition of collaboration logics. The viewpoint is structured into five domains that represent how data and controls move across the Internet Information Service: (i) control, (ii) operations, (iii) information, (iv) application, and (v) business.
- Implementation viewpoint: it describes the general architecture and focuses on technologies that are needed for the implementation of the functional components of the functional viewpoint, their communication and life cycle processes. Namely, the viewpoint defines the technological components, interfaces, protocols, and their behaviors. Coordination activities of the usage viewpoint steer these components that support the system capabilities solved by the business viewpoint.

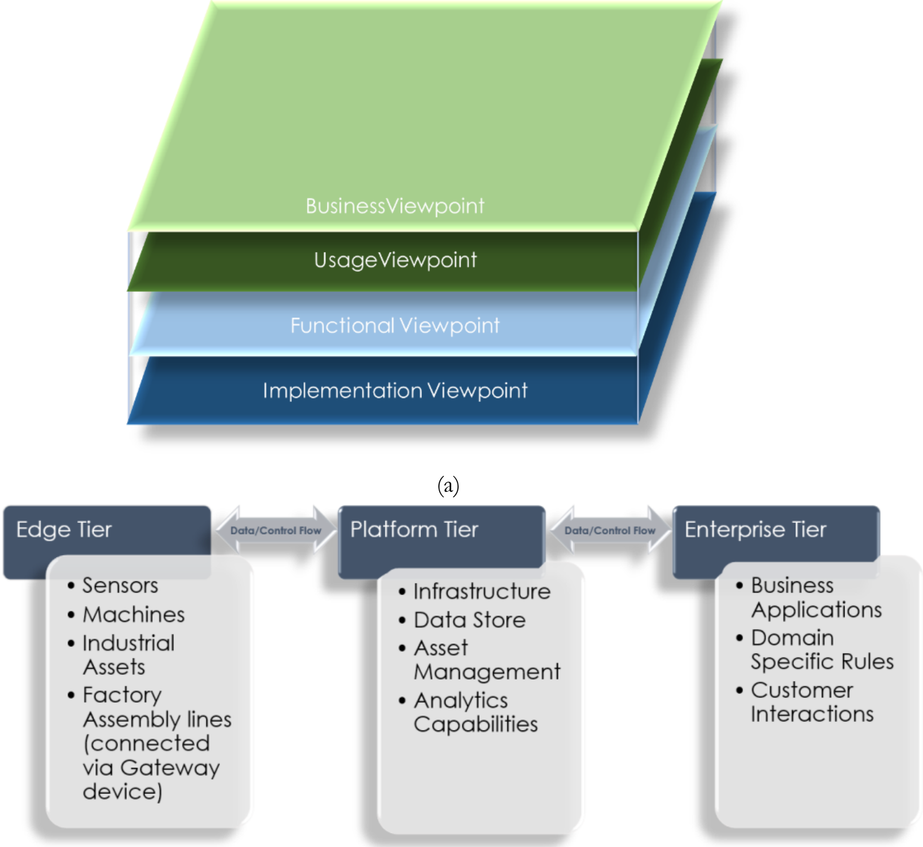
The structure is kind of hierarchical from the top viewpoint (i.e. business viewpoint) to the bottom (i.e. implementation viewpoint), since the representation follows the rule according to which decisions of the topper level address the requirements to comply with within the lower levels. A good practice to solve concern is to not solve them separately, rather than as a whole. This is all the truer since viewpoints also entail 'crosscutting concerns' which relates the whole system and therefore to more than one viewpoint. These concerns are referred to as 'crosscutting concerns'. These concerns mostly relate to system properties, which depend on both the components and the interaction between them. These system properties are named 'System Characteristics' and they are of high importance since influence the behavior of IIoT systems.

Each viewpoint is then represented by a three-tier structure mediated by three nodes of the network. Three-tier architecture is described in the bullet list below:

- Edge tier: it is responsible for collecting data from assets, sensors, and gateways, through edge nodes using the proximity network. It contains the controls domain.
- Platform tier: it links controls commands between the Enterprise tier and the Edge tier. It contains operations and information domains, as management functions, data query, and analytics for assets.

- Enterprise tier: it contains the application and business domains, namely implements decision support systems, and provides interfaces to end-users to implement specific functionality such as MES, SCM and ERP.

This process results in an abstract architecture representation (Lin, Murphy, et al., 2017). Viewpoints and tiers are depicted in Figure 3.3 adapting Lin, Miller, et al. (2017).



(a)

(b)

Figure 3.3. The IIRA representation of viewpoints (a) and tiers (b) adapting Lin, Miller, et al. (2017)

The IIRA does not refer to an owned model for cyber-physical assets as the RAMI 4.0 do, and it refers to the general concept of DT suitably represented in IIRA infrastructure, as provided in Figure 3.4. IIRA DT for virtualization of physical assets adapting (Pedone & Mezgár, 2018).

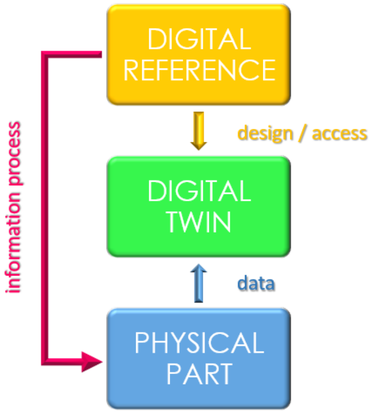


Figure 3.4. IIRA DT for virtualization of physical assets as in Pedone and Mezgár (2018)

3.1.3 Interoperability and comparison

Both standards are defined to develop smart industrial operations through (i) digital-based optimization of the industry processes and (ii) redesign of the business outcome. Main conceptual differences lie in the target to which they aim and they are described according to Lin, Murphy, et al. (2017) and (Adolphs et al., 2015).

First, while IIRA aims at a discrete number of different industries and wants to define IIoT system characteristics to promote the connection of systems involved in the processes, RAMI is mainly targeted at the manufacturing industry and aims to a step-by-step migration of old to new systems based on digitalization and integration of the VN. The IIRA defines a define technology model, although not explicitly defines the technologies to be implemented because it looks at all economic sectors regardless the specificity of their activities, e.g. oil and gas and healthcare as well. RAMI 4.0 is officially part of the political realization strategy 'Industrie 4.0' of the German Government. It puts big emphasis on providing product life-cycle information through a digital representation of assets on operations environment via the administrative shell of I4.0 components. In a nutshell, while RAMI offers a solution approach, IIRA provides less detailed means of description. Moreover, RAMI is based on existing standards, whereas IIRA is mostly motivated from practice.

The interoperability among RAs is a core topic of RA design, and even more so concerning RAMI 4.0 e IIRA since the outstanding prominence they have given to I4.0.

Interoperability is the ability of two or more systems to mutually exchange and understand information, and it is realized by using common standards at various levels of the system: for instance, in industry, standards can be technical, syntactic, semantic, conceptual or functional and business (Pedone & Mezgár, 2018). Many features of the two architectures are different and thus interoperability can allow to merge implementation of both across. The following consideration sticks to Pedone and Mezgár 2018) and to Lin, Murphy, et al. (2017).

In preliminary results from a joint work of same Industrial Internet Consortium & Plattform Industrie 4.0 (Lin, Murphy, et al., 2017), the authors showed how correspondences between ICT layers in RAMI 4.0 and functional viewpoint in IIRA do exist. Each layer of RAMI 4.0 vertical axis is paired to a domain of the Functional Viewpoint in IIRA.

Considering I4.0 component of RAMI 4.0, it is possible to link this to the DT of IIRA. DT is the digital counterpart of physical asset and allows all integration practices. I4.0 component is an object that is able to communicate independently, by using I4.0 compliant communication. This communication is possible both to embedded I4.0 components and non-native I4.0 components via the Administration Shell' that routes virtualization of physical assets. The 'Administration Shell' is the RAMI 4.0 counterpart of the IIRA DT and contains asset lifecycle, technical functionality, and the procedures for sensor data integration and monitoring. 'Virtual Representation' and 'Technical Functionality' of the RAMI 4.0 Administration Shell, whose directory is represented by its 'Manifest', are accessed via 'Component Manager' and can communicate with the 'Digital Reference' of IIRA by means of Service-oriented Architectures. Hence, although Administration Shell is devoted to integration of physical assets, while DT is more oriented towards virtualization of same assets, an alignment exists. A recap is provided in Table 3.1. Finally, a core element of interoperability among these RAs is the Open Communication

Standard Unified Architecture (OPC UA), directly specified by both IIRA and RAMI 4.0 as possible architecture for feasible integration, and IIoT service standardization of distributed industrial services[50].

Table 3.1 - Comparison between RAMI 4.0 and IIRA for interoperability

Element	**RAMI 4.0**	**IIRA**
architecture layers (RAMI 4.0) and functional domains (IIRA)	Asset layer	Physical system
	Integration layer	Control domain
	Communication layer	Network connectivity
	Information layer	Information domain
	Functional layer	Operations and Applications domains
	Business layer	Business domain
I4.0 component (RAMI 4.0) and IIRA component	Assets i.e. Things	Physical part
	Administration shell	Digital Twin
	Component Manager of Administration Shell	Digital Reference

3.2 A structured Literature Review on I4.0 RAs in systems engineering

The structured literature review here provided have been tailored to reference architecting in systems engineering, especially focusing on OM and SCM. The approach of the literature review is both quantitative and qualitative, according to definition provided by (Curry, Nembhard, & Bradley, 2009). The quantitative analysis relates to the frequencies of defined indicators that addresses the state-of-the-art of the field. Documents are then briefly outlined for describing the structures and characteristics of the RAs provided. Figure 3.5 introduces and clarifies the framework adopted, adapted from Webster and Watson (2002), for obtaining a final database of 65 documents to qualitatively review. These are 41 RAs obtained directly by the query strings plus 24 RAs coming from literature reviews of paper suitable to the analysis.

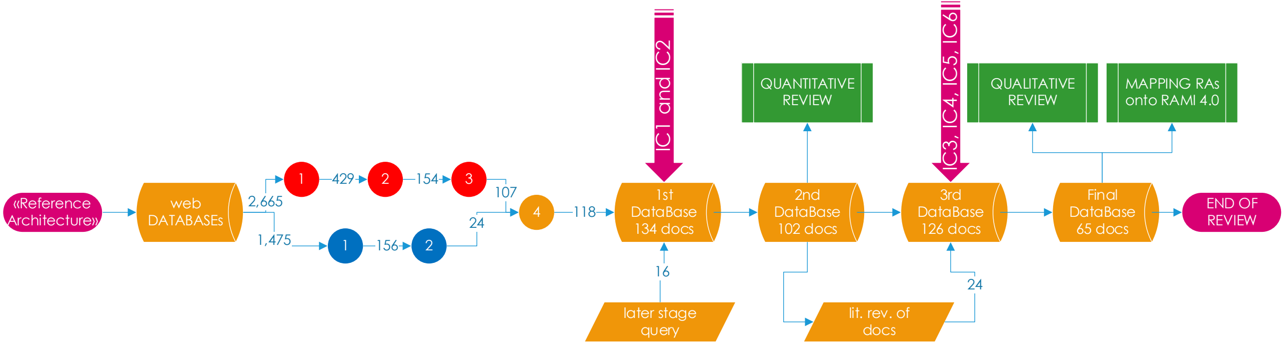


Figure 3.5. Framework for deriving the literature database to analyze

Two main abstract and paper databases of peer reviewed literature, namely Scopus and Web of Science, have been queried. The query strings are provided at the end of the thesis[i]. These 65 documents all meet inclusion criteria defined, that are discussed in steps of analysis in which they are formulated. Each stage of the framework is fully commented when it is approached. In the figure, yellow servers represent databases, keys for limiting the query string are represented by numbered nodes, counts on the arrows

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[50] Source: Prepare for the New Era of IIoT using OPC UA Connectivity. Retrieved from: https://www.arcweb.com/blog/prepare-new-era-automation-using-opc-ua-connectivity. Last access: 2020.09.18

represent the documents available according to the new string. The red-colored nodes represent result from the query on Scopus. The query on Web of Science is represented in blue-colored nodes. Yellow-colored node represent the duplicate elimination. Documents suitable for the analysis are represented by numbers reported in the suitable databases. The inclusion criteria to meet that limit the suitability of documents are illustrated by means of vertical arrows in purple font. Documents added externally from the querying process are showed by yellow parallelograms.

The query strings have been formulated on 2019.10.14 and starting from a complex of more than 4,000 documents whose meta-file contained the term 'Reference Architecture', tailoring the search query first to 'Industry 4.0' and terms sometimes used as synonyms, namely 'Smart Manufacturing', 'IoT', 'Internet of things', 'Industrial Internet of Things', 'IoT', 'IIoT', and 'Industrial Internet'. This step is realized at node 1. Then, results are tailored to 'Engineering' field, i.e. node 2. Next, results are narrowed to 'Manufacturing', 'Production', and 'Supply Chain Management', i.e. node 3 on Scopus, whereas on Web of Sciences it is realized at node 2 since a different query search tool. Finally, duplicates are eliminated, i.e. node 4. 118 results have been listed. Further, have been added 16 documents retrieved querying same databases in the first middle of 2020, for total 134 documents. As it could be stated from chart in Figure 3.6, the research interest has spread over years. Of course, the count of research in 2020 is affected by the partial results given by querying the databases only after some months of the year.

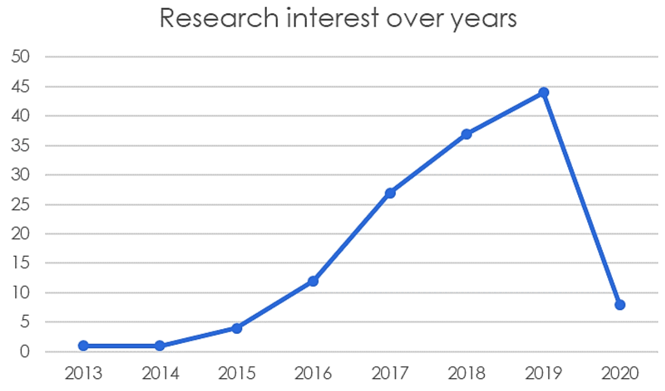

Figure 3.6. Research interest growing over years. Results from 2020 are biased by date in which databases have been queried

The most important publisher is the Institute of Electrical and Electronics Engineering (IEEE) to which belong almost 60 publications. IEEE has achieved more than 1,350 citations over years for works considered. Figure 3.7 provides the overview of journals and publishers involved in the analysis. If journals do not belong to same publisher, they are directly mentioned; otherwise, the publisher clusters more than a single journal. Names of the publishers are normalized, e.g. proceedings of IEEE conferences as well as IEEE journals are labeled as 'IEEE'. The same applies to CIRP journals and proceedings, labeled as 'CIRP'. Number of citations obtained over years for the works considered is counted in the labels over bars.

The list of 134 documents has then reduced considering the following inclusion criteria:

IC1. Document must be available on the web
IC2. Document must be in English language

An amount of 102 documents meets IC1 and IC2 out of 134 documents. From these documents it is possible to identify (i) the industries to which the RAs are addressed and the focus on which authors have provided, and (ii) the evolution of the field considering how the study are changed over years.

Concerning the industries, as it emerges from Figure 3.8, the majority of studies are interesting on general industrial sectors, as well as manufacturing industry, namely they both cover almost 50% apiece. The difference to 100% is covered by other industries, and only automotive industry overcome the 1% limit (i.e. 3% of the total).

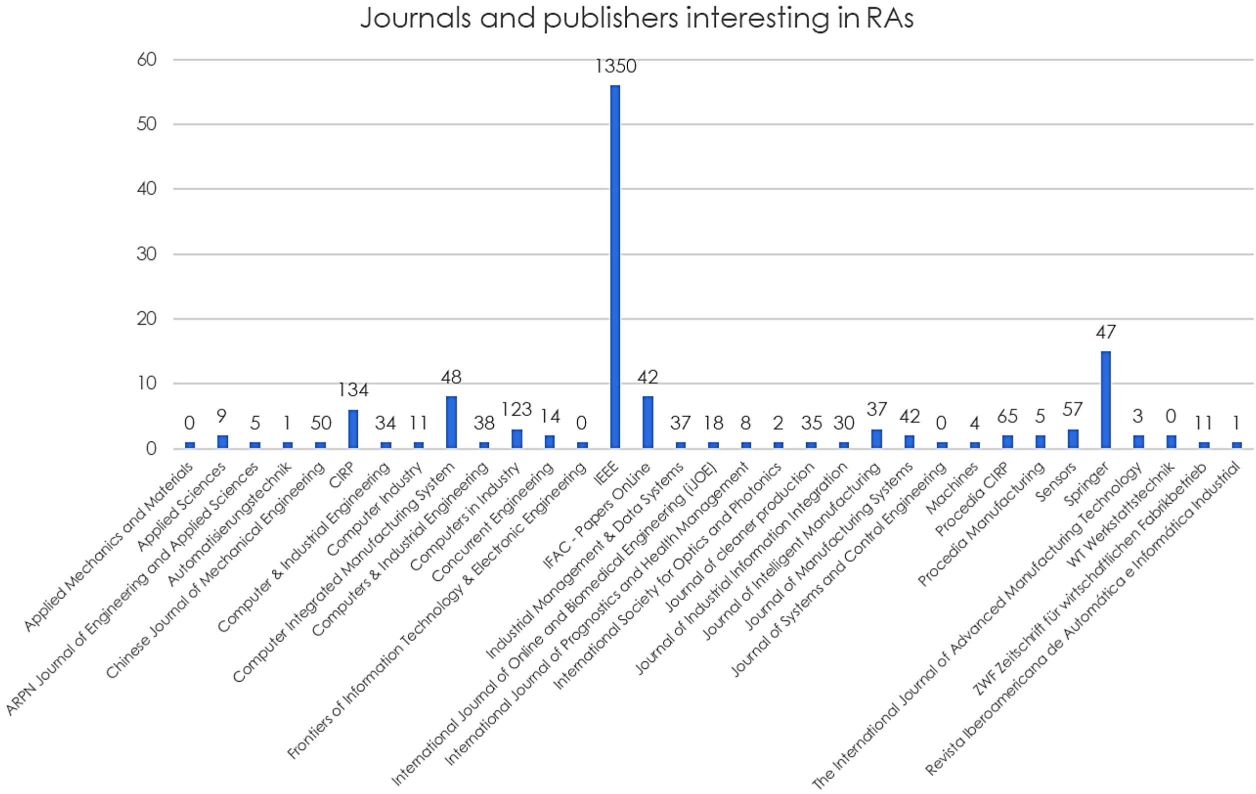

Figure 3.7. Publishers and journals interesting in RAs and citations achieved over years (provided in the label on top of the bars)

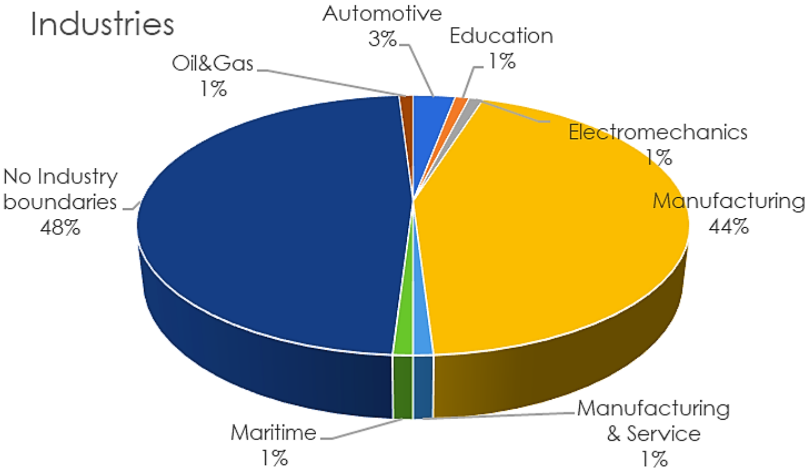

Figure 3.8. Industries to which RAs are directed

Concerning the focus on which authors have paid their attention, from Figure 3.9 it is arguable that the most of studies have discussed general-purpose RAs. Concerning specific applications at which aiming attention, integration of systems (i.e. 10%) and maintenance (i.e. 9%) triggered studies more than other fields. RAs for SFs and CPPS follow (7% and 5%, respectively), as well as studies concerning safety and security issues of I4.0 (i.e. 6%). It has to be said that almost 10% of studies (i.e. 9 out of 102 documents) are reviews of other models. Thus, an analysis of what kind of study authors have been provided is here carried out. The studies are judged on the basis a 0-1 scale of values, in which:

- Values ranging from 0.1 to 0.4 are attributed to studies discussing RAs
- Values ranging from 0.6 to 1 are attributed to studies designing RAs
- Middle value 0.5 is neglected

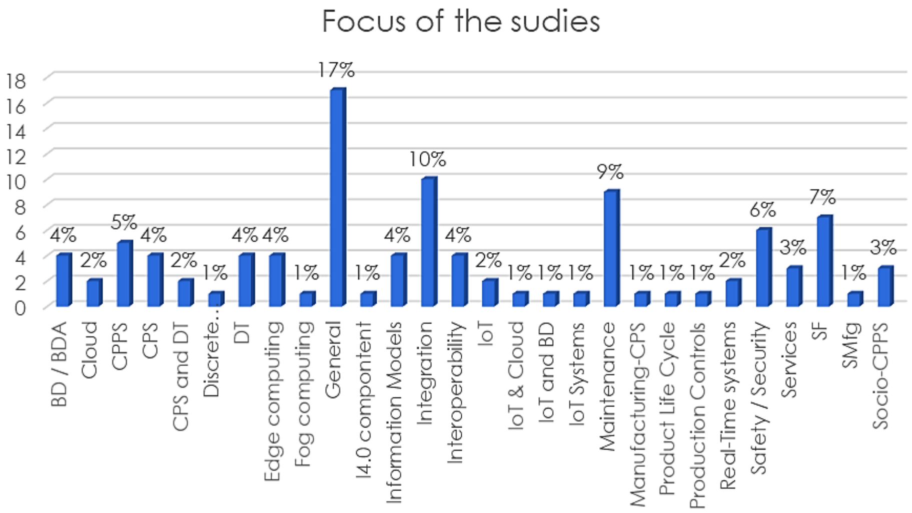

Figure 3.9. Focus of the studies on RAs

The full scale of judgement is provided in Table 3.2. Concerning RA designs, two type of RAs characterize the identification of study typologies, each one characterized by two subtypes of functions:

- 'Single purpose' RAs:
    - studies that provide RAs for specific applications (e.g. maintenance) and focusing on specific aspects of the application (e.g. data and information flows)
    - studies providing RAs for specific applications discussing all its issues and functions
- 'General purpose' RAs:
    - studies that provide a general RA to be used regardless specific applications
    - studies that provide a general RA providing the blueprint of I4.0 system architecture

Table 3.2 - Scale of judgement for attributing typology label to studies on RAs

Type of study	Value	Meaning
Discussing RAs	**0.1**	*introducing the need for a RA*
	0.2	*quantitative literature review*
	0.3	*comparison of RAs*
	0.4	*RA comprehensive description/extending the solution*
Designing a RAs	**0.6**	*introducing the solution/applying another RA*
	0.7	*single purpose solution (e.g. threating data for maintenance systems)*
	0.8	*holistic single purpose solution (e.g. devoted to realizing an omni comprehensive maintenance solution)*
	0.9	*general-purpose solution for industrial and business practices (i.e. regardless specific applications)*
	1	*holistic RA*

Results are provided in Figure 3.10 by means of a bubble chart in which the size of the bubbles relates to number of occurrences of each study typology. As it can be argued, it has been switched over years from simply reviewing RAs already provided, usually by working group or systems engineering practitioners, to providing general-purpose solutions. Very few studies have provided holistic RAs.

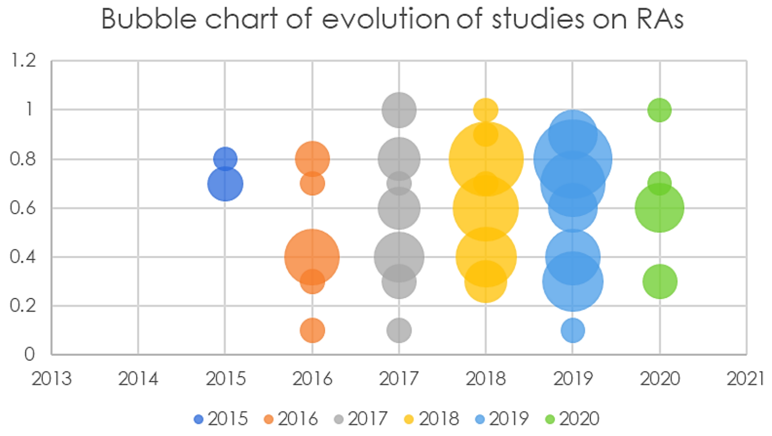

Figure 3.10. Bubble chart of evolution of studies on RAs. Size of the bubbles relates to number of occurrences

Following to this analysis, it has been analyzed the distribution of values and quartiles grouping them, as evolved over years. A box and whiskers plot has been used, as in Figure 3.11. The box is limited on the bottom form values lower than the 1st quartile (i.e. 25% of values), and on top by values greater than 3rd quartile (i.e. 75% of values). Upper and lower whiskers identify max and minimum values calculated by the software according to the following computations:

$$Max\ value = Q_3 + 1.5 * (Q_3 - Q_1)$$
$$Min\ value = Q_1 - 1.5 * (Q_3 - Q_1)$$

Median is showed by internal line in the box. It can be argued that although they are some years that researchers are studying RAs, the majority are interesting in applying other RAs already designed (i.e. median value lower than 0.6 until 2018), and just recently (i.e. 2019) the majority of studies are providing new RAs, especially for specific applications (i.e. median value 0.8). For both graphs in Figure 3.10 and Figure 3.11, results for 2020 are biased by the partial quantity of studies analyzed.

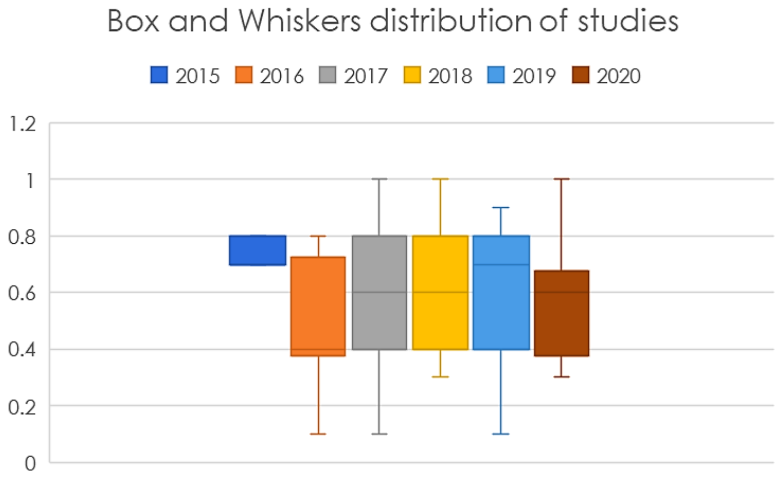

Figure 3.11. Box and whiskers plot for distribution of values. Line in the box show the median of distribution

The further step of analysis of RAs already provided in literature, concerns the qualitative review of available models, which is provided in the next subsection. The methodology for retrieving documents is here described.

By skimming sources available on the web, from the literature review available, it is possible to retrieve further 24 documents providing RAs for I4.0 functionalities. Then 126 documents are further reduced considering the following inclusion criteria:

IC3. Documents out of scope are disregarded. For being labeled out of scope, the document must meet one of the following criteria:
   a. The study is a literature review that does not provide new RA
   b. RA is designed for fields different from OM and SCM of systems engineering, e.g. RAs for energy saving or environmental sustainability
   c. Topics related to RAs are discussed, but a new RA is not provided, e.g. design of platforms for integrating RAs, as well as practical application of already provided RAs

IC4. Document must be available on the web

IC5. Document must be in English language

IC6. Documents out of scope are disregarded. For being labeled out of scope, the document must meet one of the following criteria:
   a. The study is a literature review that does not provide new RA
   b. RA is designed for fields different from OM and SCM of systems engineering, e.g. RAs for energy saving or environmental sustainability
   c. Topics related to RAs are discussed, but a new RA is not provided, e.g. design of platforms for integrating RAs, as well as practical application of already provided RAs

A final database of 65 documents to be qualitatively retrieved is obtained.

Finally, a mixed quali-quantitative approach has been performed for mapping 65 RAs onto RAMI 4.0.

3.2.1 The qualitative analysis of literature on RAs

In the following qualitative review, the lexicon adopted for describing the studies is used accordingly to the authors of original studies. For the acronyms, refer to the original works. 'ID' refers to the label with which works are listed in the tables in Appendixes. The IIRA (Lin, Miller, et al., 2017) (ID 6.4) is not here cited, albeit it is inserted in the tables, since it has been already discussed in the previous section.

The first group of studies belongs to academia research.

Liu, Tong, Mao, and Yang (2019) (ID 1) propose a RA for smart factory and its application path for traditional manufacturing enterprises in China, based on an analysis of 5G and IoT. The IoT is combined with BD and network infrastructures and platforms for designing the real-time tracking and monitoring system of intelligent workshop products.

Sarabia-Jácome, Palau, Esteve, and Boronat (2019) (ID 5) present the Seaport Data Space (SDS) based on the Industrial Data Space (IDS) RA model to enable a secure data sharing space and promote an intelligent transport multimodal terminal. The architecture is meant for sharing BD with Electronic Data Interchange and Port Community System platforms; thus, a higher BD architecture is integrated to manage these data.

Maple et al. (2019) (ID 12) propose a RA using a hybrid Functional-Communication viewpoint for specific cyber security functionalities of Connected Autonomous Vehicles. The RA includes the devices, Edge and Cloud systems interact with the vehicles. Two case studies are provided.

Larrinaga et al. (2019) (ID 13) present the implementation of a RA for cyber-physical systems to support condition-based maintenance of industrial assets. It also provides a practical use case describing the data analysis approach to manage predictive maintenance using MANTIS RA (Hegedűs, Varga, & Moldován, 2018).

Helo and Hao (2019) (ID 18) propose a reference implementation of blockchain-base logistics monitoring and its test based on Ethereum platform with the purpose of demonstrating how blockchain can be implemented in the operations and supply chain context by using software components.

The '5C architecture' of Lee, Bagheri, et al. (2015) (ID 19.1) is provided for guidelines of CPS actual implementation. The architecture is discussed in the next section in which the view stack components of a new RM is discussed.

Yli-Ojanperä, Sierla, Papakonstantinou, and Vyatkin (2019) (ID 20) review RAs in I4.0 and stresses the outbound communication functionality of RAMI 4.0 by means of further adoption of OPC UA.

Al-Gumaei et al. (2019) (ID 21) define requirements for designing an analytics platform for industrial BD and then design a BD RAs for industrial machine learning applications. The RA is compared to other similar, and then tested towards reliability and scalability.

Yamato, Kumazaki, and Fukumoto (2016) (ID 21.2) provide an architecture concept by which they propose a maintenance platform. In this platform, edge nodes analyze sensing data, detect anomaly, extract a new detection rule in real time and a cloud orders maintenance automatically, also analyzes whole data collected by batch process in detail, updates learning model of edge nodes to improve analysis accuracy.

Wan et al. (2017) (ID 21.3) propose and implement a manufacturing big data solution for active preventive maintenance in manufacturing environments. A system architecture active preventive maintenance is designed. BD are collected and subsequently processed in the cloud in real-time. A prototype platform implements experiments to compare the traditionally used method with the proposed active preventive maintenance method.

Wu, Lu, and Zhang (2019) (ID 22) propose a RA for CPSs of fractal manufacturing, towards transforming the manufacturing requirements into reconfigurable rules to organize the fractals, for ultimately achieving customized production process. The RA is tested by a case study of automotive manufacturing process.

Jiang et al. (2019) (ID 24) proposes a RA for specific socio-CPSs enabled by IDS. A practical example is conducted to validate the architecture.

Neal, Sharpe, Conway, and West (2019) (ID 25) provide a CPS RA for monitoring work in process. The study concludes with a feasibility study for verifying service provided to CPS and monitoring of logistical handling process.

The PROSA architecture (ID 7.1) has been designed for holonic manufacturing systems, and it has developed in the further ARTI architecture (Valckenaers, 2018), which seems to be more a RM for making intelligent systems.

Kang, Lee, and Noh (2019) (ID 28) propose a logic-based systematic methodology that can generate a throughput analysis model from the real-time data of a shop floor in a CPPS environment. Furthermore, logics that perform the Mapping, Scaling, and Calibration of the data of the shop floor into the machine, process, and factory levels is developed. Finally, a throughput analysis is described by means of a case study.

Koziolek, Burger, Platenius-Mohr, Rückert, and Stomberg (2019) (ID 34) introduce an open 'Plug-and-Produce' RA as a template for practitioners implementing IIoT, for automating the configuration and integration tasks of industrial controls systems. A study case demonstrates that the RA allows to reduce the configuration and integration efforts for easily scaling up towards IIoT systems.

Corradi et al. (2018) (ID 36) report about an actual use case of a network of 12,000 ice cream machines connected worldwide by an architecture anticipating-and-similar to RAMI 4.0. Further stress on interoperability is highlighted.

Yoon, Um, Suh, Stroud, and Yoon (2019) (ID 38) propose a RA for the information service bus or middleware for the SF that can be used for information acquisition, analysis, and application for the various stakeholders at the levels of machine, factory, and ERP. The RA is based on industrial issues identified and transformed into requirements.

Redelinghuys, Basson, and Kruger (2019) (ID 40) present a RA for DT, for exchanging data and information between a remote emulation or simulation and the physical twin. The architecture is structured in different layers, including a local data layer, an IoT Gateway layer, cloud-based databases and a layer containing propertied of digital side of DT. The RA wants to provide a service-based and real-time enabled infrastructure for vertical and horizontal integration. A test in a SMEs is performed.

Cupek, Drewniak, Ziebinski, and Fojcik (2019) (ID 41) propose how ISA 95 automation pyramid can be transformed into a RA model (RAM) for I4.0. An actual use case is described

Trabesinger, Pichler, Schall, and Gfrerer (2019) (ID 42) provide a RA for integrating smart devices into CPPS.

Oks, Jalowski, Fritzsche, and Möslein (2019) (ID 43) derive a RA for designing demonstrators for industrial CPS. An application is provided by means of a suitable platform.

Qi and Tao (2019) (ID 45) introduce a hierarchy RA for SMfg based on cloud computing, fog computing, and edge computing. The architecture is at DT shop floor. Authors also describe the view of a 'Cloud-based manufacturing system architecture', as a combination of cloud-based design and manufacturing services integrated for provision of new services and technologies. This

Landolfi, Barni, Izzo, Fontana, and Bettoni (2019) (ID 46) describe an architecture for Manufacturing as a Service, creating an ecosystem that acts as a virtual marketplace bringing production capacity, as well as other virtual and physical assets, closer to the production demand, to obtain their optimal matching. Sustainability perspective is pursued. As a data rich platform, it integrates the IDS connector to link different entities through secure exchange and trusted sharing of data (i.e. data sovereignty).

Kosak, Wanninger, Hoffmann, Ponsar, and Reif (2019) (ID 47) present a RA for mobile robots for integrating different sensors and actuators. Interoperability with previous robot environments is considered. A real-world experiment as well as one in a simulation environment are tested.

Montavon, Peterek, and Schmitt (2019) (ID 48) provide a RA for data fusion collected by different sensors, actuators, and more in general, metrology instruments.

Yasmin et al. (2018) (ID 50) propose an application of augmented reality in an IoT infrastructure, for condition-based maintenance. The implemented application visualizes environmental conditions and the sensor node itself as an augmented object. A user study is carried out to discuss and showcase the potential impacts of using such a visualization approach.

Buenabad-Chavez, Kecskemeti, Tountopoulos, Kavakli, and Sakellariou (2018) (ID 51) present an analysis of the RAMI 4.0 service hierarchy, compared to traditional service-oriented architecture, towards a methodology for the design of RAMI 4.0 services based on object-oriented analysis and design principles. Similarity between objects and assets of these architectures.

Tountopoulos, Kavakli, and Sakellariou (2018) (ID 52) discuss the role and significance of data in the management of manufacturing operations and proposes a RA for controlling the orchestration of data services.

The IoT Architecture Reference Model of Bassi et al. (2013) (ID 53.1) reverses the process of designing a RM. System architecture can interoperate with this RAM avoiding incompatible language and system partitions and mappings. The differences not solved are those relating to lack of interoperability. The characteristic is achieved by defining qualitative system requirements that addresses in what two architectures differ. The RAM is designed leveraging the IoT RM of (Martin Bauer et al., 2013) (ID 65.4) and the IoT RA of (M. Bauer et al., 2013) (ID 56.5).

Vucnik et al. (2018) (ID 54) provide a RA and implementation of a framework for testbed infrastructures within multi-technology 5G networks. The implementation upgrades an existing wireless experimentation testbed (Fortuna, Bekan, Javornik, Cerar, & Mohorcic, 2017; Šolc, Fortuna, & Mohorčič, 2015) with new software and hardware functionalities such as web service technology and operating system virtualization technologies, via wireless networks of IoT.

Balogh, Gatial, Barbosa, Leitão, and Matejka (2018) (ID 55) propose a reference architecture on the basis of an IoT infrastructure for the collection of the huge amount of available shop floor data, analyzed by data analytics algorithms, predictive maintenance models and forecasting techniques, to perform predictive maintenance interventions.

Da Xu, He, and Li (2014) (ID 56.2) have designed a RA for providing services via network of sensing components. Interface realize the service provision.

Ye and Hong (2018) (ID 59) develop a four-layer architecture for manufacturing system similar to RAMI 4.0. Additionally, an experimental system is constructed to demonstrate the availability and applicability of the proposed approach.

Lu, Riddick, and Ivezic (2016) (ID 61.2) introduce a service oriented SMfg RA modelled with DT, IoT, and CPPS.

Pedone and Mezgár (2018) (ID 63) identify challenges of inventory-management based supply in the automotive industry from the aspect of I4.0 solutions. Solution is based on cyber physical logistics systems for just-in-sequence supply and RAMI 4.0.

Otto et al. (2017) (ID 67.1) provide the IDS Architecture Model[51] which is divided into five layers, Business, Functional, Process, Information, and System, to which correspond decreasing level of abstraction of industrial entities.

Illa and Padhi (2018) (ID 76) provide guidance to transform legacy manufacturing units to SFs of I4.0 by means of a RA discussed by practical approaches.

Erasmus, Grefen, Vanderfeesten, and Traganos (2018) (ID 77) present the architecture design of an information system that integrates Cloud, IoT, and smart devices to support hybrid manufacturing processes, i.e., processes in which human and robotic workers collaborate. The resulting information

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[51] Retrieved in Alonso, Pozo, Cantera, De la Vega, and Hierro (2018)

system architecture model is proposed as a RA for a manufacturing operations management system for I4.0.

Chakravorti et al. (2018) (ID 84) provide an industrial demonstrator to implement a Data Analytics tool that provides rules beneficial for root cause analysis and a decision support system for early prediction of the failures. The tool also identifies key alarms for monitoring the machine condition.

Helu, Hedberg Jr, and Feeney (2017) (ID 92) present a four-tiered RA designed to manage the data generated by manufacturing systems for the digital thread. The architecture provides secured access to internal and external customers, which protects intellectual property and other sensitive information, and enables the fusion of manufacturing and other product lifecycle data. An implementation with a contract manufacturer is provided.

Montavon, Peterek, and Schmitt (2017) (ID 93) propose a three-layer model consisting of an interface to the sensor systems, a middle layer managing the allocation and transition between the individual devices and a top layer representing the user interface. OPC UA is used for implementation of the prototype.

Gröger et al. (2016) (ID 105.1) introduce the SITAM[52] architecture that encompasses the entire 'industry product life cycle': processes, physical resources. Among these, CPS and machines, IT systems as well as web data sources. The architecture is IT-value adding based, and two middleware layers link the real-world to IT service. Data Quality, Governance, and Security viewpoints realize the continuous improvement and feedback process.

Westermann, Anacker, Dumitrescu, and Czaja (2016) (ID 113) provide a RA in combination with maturity levels for CPS.

Yoon and Suh (2016) (ID 122) focus on the manufacturing information bus from the perspective of cyber-physical manufacturing system, hence develops a RA for the manufacturing information bus for the SF that can be used for information acquisition, analysis, and application for the various stakeholders at the levels of Machine, Factory, and ERP. A practical implementation process of the RA is presented and demonstrated by means of a case study.

O'Donovan, Bruton, and O'Sullivan (2016) (ID 123) present a formal industrial analytics methodology that may be used to inform the development of industrial analytics capabilities across multidisciplinary department of enterprises. A technology RA is provided. The proposed methodology is demonstrated in a case study, where an industrial analytics platform is used to identify an operational issue in a large-scale.

Bordel Sánchez et al. (2015) (ID 126) propose a general theoretical framework for traceability systems, hence propose a RA based on SMEs requirements. A first minimum functional prototype is proposed to compare the solution to a traditional tag-based traceability system.

Sayed, Lohse, Søndberg-Jeppesen, and Madsen (2015) (ID 127) propose a RA that aims to enable the provisioning of diagnostic and prognostic capabilities in manufacturing systems that utilize smart devices for automation.

Kassner, Gröger, Mitschang, and Westkämper (2015) (ID 128) present a product life cycle analytics approach for the total integration and analysis of unstructured and structured data from multiple data sources brought by the product life cycle. A set of requirements for a RA are defined, as well as an application scenario, and a strategy towards implementation.

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[52] Retrieved in Kassner et al. (2016)

Stoyanov and Rusev (2019) (ID 133) present a RA which aims at integrating virtual and physical worlds to support the virtualization of physical object. The integration function is supported by a component called the 'Guard system'. The architecture proposed refers to the 'Guard system'. An application to the intelligent agriculture system tests the 'Guard system'.

B. Chen et al. (2017) (ID 134) provide a three-hierarchy level architecture of the smart factory, then the key technologies were analyzed from the aspects of the physical resource layer, the network layer, and the data application layer. A candy packing line is used to verify the key technologies (IoT, BD, and Cloud Computing) of SF.

Other RAs are provided by consortia, international funded projects, working groups, and other professionals and practitioners' groups. These are introduced in the next second group.

Standardization institutions also deal with providing RAs. The ISO/IEC 30141:2018 IoT RA[53] (ID 14.1) uses a top-down approach, modelling a RA for an architecture in five architecture views starting from characteristics of IoT further abstracting into a generic IoT Conceptual Model. The National Institute of Standards and Technologies also have provided the NIST Reference CPS Architecture[54] (ID 126.1), that realizes the view of 'co-engineered interacting networks of physical and computational components'. The RA is composed of hierarchical IT layers (from asset to business applications) and different views which express the service to provide and features to meet (e.g. interoperability, security).

One of the most adopted concept to which apply RA is the edge computing. Bandyopadhyay and Sen (2011) (ID 56.1) provide a RA consisting in two blocs, relating to data capturing and data utilization. The same edge is the backbone of the IoT RM[55] (ID 56.3), which deals with data ingestion and transformation from physical devices to cyber applications. The FAR-EDGE architecture (ID 6.1) is a RA for decentralized IoT and CPS controls, leveraging fog computing, edge computing, and cloud computing for scalable and advanced manufacturing systems implementing techniques for automation systems and production resources. It has been designed within the international funded FAR-EDGE project[56], which has also produced a comparison of RA (Sittón-Candanedo et al., 2019) for validating the FAR-EDGE architecture. Another consortium that has produced a RA of edge computing is the Edge Computing Consortium[57] of several organizations (e.g. Chinese Academy of Science, and Intel). The Edge Computing Reference Architecture 2.0 (ID 6.2) develops following a layer model both horizontally and vertically, using open interfaces services and data life-cycle services, respectively. A further analysis on edge architecture preparatory for consequent development of an RA has been also carried out by the IIC (M. Tseng, Canaran, & Canaran, 2018) (ID 6.3). The IIC is the same consortium which has also developed the IIRA (Lin, Miller, et al., 2017) discussed in the previous section. Furthermore, to IIC is related the OpenFog Consortium which has designer the OpenFog RA[58] (ID 23.2) intended to help business leaders, software developers, system designers and professionals to create and maintain the hardware, software, and system elements necessary for fog computing, an extension of the cloud

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[53] Source: ISO/IEC 30141:2018. Internet of Things (IoT)—Reference Architecture. National Standards of America. Retrieved in Yuan, Chen, Xu, and Chen (2019)

[54] Retrieved in Bordel Sánchez et al. (2015)

[55] Visit: http://cdn.iotwf.com/resources/71/IoT_Reference_Model_White_Paper_June_4_2014.pdf. Last access: 2020.09.19

[56] FAR-EDGE Project: FAR-EDGE Project H2020 (2017). Visit: http://far-edge.eu/#/. Currently not available on the web

[57] Edge Computing Consortium, Alliance of Industrial Internet: Edge Computing Reference Architecture 2.0. Technical report, Edge Computing Consortium (2017). Available from: http://en.ecconsortium.net/Uploads/file/20180328/1522232376480704.pdf. Last access: 2020.10.19

[58] Visit: https://www.iiconsortium.org/pdf/OpenFog_Reference_Architecture_2_09_17.pdf. Last access: 2020.09.19

computing model. The RA is aimed at security, scalability, openness, autonomy, reliability, availability and 'serviceability', agility, hierarchy, and programmability. It is somehow similar to edge computing, while edge computing does not entail cloud functionalities. Cloud, edge, and their integration and orchestration are the basis of the RA provided by the World Wide Web Consortium, namely the Web of Things RA[59] (ID 23.3).

Other works exist. The MIDIH RA (ID 40.2) is a RA aimed at SF and SP, consisting of six layers which realizes the digitalization and integration of product and shop floor by means of industrial IoT and industrial analytics[60]. Finally, the IBM[61] (ID 61.1) published a two-layer reference architecture for Industry 4.0 for describing the functional architecture of a manufacturing system. Two layers relates to devices and cloud for collecting and managing data.

3.2.2 Mapping RAs onto RAMI 4.0

The further step of the quali-quantitative review entails mapping 65 RAs retrieved onto RAMI 4.0. The quantitative visualization is provided in Figure 3.12, while the individual qualitative characterization of studies is provided in Table 3.6 in Appendix 3-A.

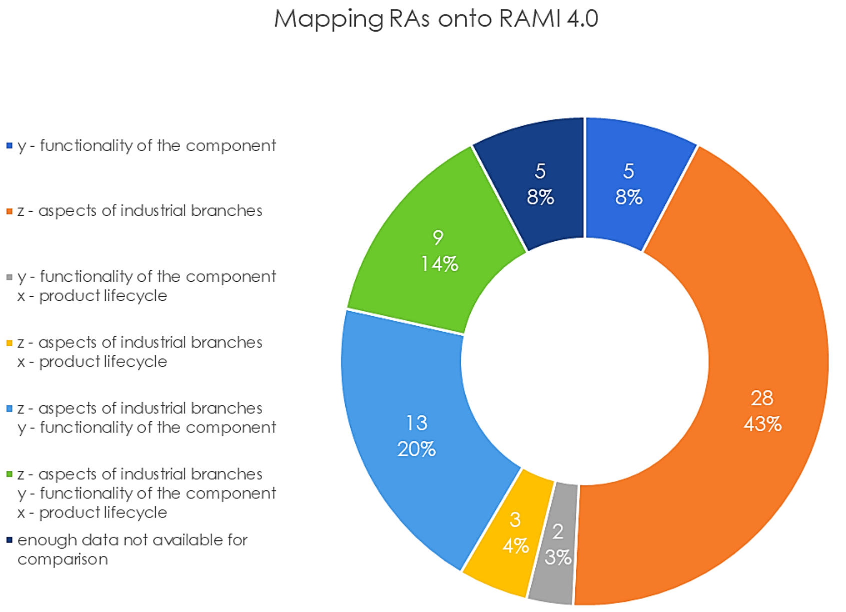

Figure 3.12. Mapping 65 RAs onto RAMI 4.0: occurrences of perspectives covered

Six possible combinations are defined:

1. 'x - product lifecycle' - the RA analyzed is focused on product lifecycle perspective as discussed in RAMI 4.0, namely can be mapped onto the RAMI x axis.
2. 'y - functionality of the component' - the RA analyzed is focused on IT functionality of I4.0 components perspective as discussed in RAMI 4.0, namely can be mapped onto the RAMI y axis.
3. 'z - aspects of industrial branches' - the RA analyzed is focused on perspective as discussed in RAMI 4.0, namely can be mapped onto the RAMI z axis.

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[59] Visit: https://www.w3.org/TR/wot-architecture/#introduction. Last access: 2020.09.19

[60] Visit: https://midih.eu/documents/MIDIH%20Reference%20architecture.pdf. Last access: 2020.09.19

[61] Retrieved in Moghaddam, Cadavid, Kenley, and Deshmukh (2018)

4. 'y - functionality of the component' & 'x - product lifecycle' - the RA analyzed is focused on both product lifecycle and functionality of the component perspectives as discussed in RAMI 4.0, namely can be mapped onto the RAMI x and y axes.
5. 'z - aspects of industrial branches' & 'x - product lifecycle' - the RA analyzed is focused on both product lifecycle and aspects of industrial branches perspectives as discussed in RAMI 4.0, namely can be mapped onto the RAMI x and z axes.
6. 'y - functionality of the component' & 'z - aspects of industrial branches' - the RA analyzed is focused on both aspects of industrial branches and functionality of the component perspectives as discussed in RAMI 4.0, namely can be mapped onto the RAMI z and y axes.

Total 60 RAs out of 65 can be mapped this way. Only 5 RAs does not provide enough information for such a comparison. As a result, the majority of studies focuses on IT functionalities of industrial branches, namely develops RAs that meet the y axis of RAMI 4.0.

3.2.3 Discussion of results

In this section it has been provided a thorough analysis of the state-of-the-art of research, especially from academia, on RAs. More than 150 documents are analyzed, and some results can be addressed.

The academic research on RA for I4.0 is still 'almost young', meaning that it has started in 2014. Moreover, considering the quantitative result of documents retrieved, for instance, from Scopus, it is possible to argue that 135 documents obtained by querying the database about RAs and I4.0 out of total 2,665 documents on RAs, are a 5% share. That sounds as academia, concerning dealing with RAs, has a long way to go. Furthermore, lots of models are named RAs but they rather are other kind of system architecture, namely they have been retrieved RMs, frameworks, methodologies, and real architecture however named as RAs. This aspect confirms that confusion still exist.

For further stressing a kind of gap between academia and practitioners' modelling, it is possible to compare the nature of works. A large quantity of academia study has dealt with reviewing, comparing, and applying other RAs and architectures, especially from practitioner's world, at least until two years ago. With this respect, it must be stated that the suitability of comparing those RAs somehow makes space for interoperability, that is a prerequisite for the effectiveness of an RA. For instance, consideration to RAMI 4.0 and interoperability come from the analysis carried out in section 3.1. Moreover, when academia reviews literature on RAs, it generally deals with comparison as well as description provisioning towards actual applications in practical environment. Thus, also this kind of work sounds worth doing. However, while practitioners' studies seem to be tailored for large-scale adoption, academia applications seem more calibrated on small-scale test for just validating the RA.

Concerning comparison of RAs, the one carried out in this thesis about RAs interoperability with RAMI 4.0 has a twofold reason. Firstly, has to be considered that RAMI 4.0 is a kind of guideline for developing RAs and architectures. In fact, 8 studies directly mention RAMI 4.0 in their approach to designing, comparing, implementing RAs, which is the 12% of 65 studies analyzed. The amount increases to 35 documents out of 134 if is considered the original database built by querying Scopus and Web of Science (which considers also studies that do not meet inclusion criteria such as those excluding literature reviews or in other language). This sounds as 26% of studies, a relevant amount since the variety of systems engineering applications. The other reason is that such a comparison allows to understand directions to which studies have pointed so far. As a result of the analysis, RAs are mainly aimed at coping with IT functionalities of business. This is supposed because of two reason: the first one, the SF digital transformation of I4.0 has an ICT basis. The second: coping with this perspective, not only specific aspect of business are realized (e.g. systems controls of shoo floor), rather than its all perspectives. In fact, this axis realizes all different viewpoints expressed by RAMI 4.0 (Kannengiesser & Müller, 2018). Deeper insights to this statement are provided in section 3.3.3 when discussing how the new RM provided meets the RAMI 4.0.

Finally, two consideration on target of RA. Firstly, they seem to lack organic and largely debated study for development of RAs towards SMEs need. This is a gap to academia and practitioners' study in the same way. Secondly, the general nature of modelling seems to fight with I4.0 principles. Namely, it is well accepted that ne nature of I4.0 technology and functionality stack is networked (Moghaddam, Cadavid, Kenley, & Deshmukh, 2018), while generally RA adopt hierarchy structures of systems automation and control models. Although this seems to be contradictory, it is supposed to be necessary for making RA and architecture interoperable with existing systems. Furthermore, a higher level of abstraction (e.g. RM, model) is supposed to better overcome this inconsistency, since the remoteness from the actual implementation.

3.3 A new RM of I4.0 for SMEs: the RMI4.0

This thesis wants to provide a RM for practical technology implementations in SME systems and network. RM is preference because of its higher level of abstraction of SF and I4.0 system. Since the focus on technology implementation, the RM is provided in the form of technical architecture model, although a functional viewpoint is provided apart. Technical and functional representation are both needed for giving a comprehensive description of the system design (Buede & Miller, 2016). The RM here designed, i.e. 'Reference Model for I4.0' RMI4.0, wants to foster the design of I4.0 architectures, especially for SMEs. The architecture leverages the analysis of technologies addressing the I4.0 r/evolution in industrial systems (namely the SF) carried on in Chapter 2, namely BD and BDA, CPS, and IoT. It must be defined the relations among the technologies for providing a suitable representation. The research on how each technology matches each other has a literature approach: works on these technologies are analyzed and findings discovered are used for disclosing the technology stack. The works looks like a narrative review of literature. Functional viewpoint, also, is built by means of notable architectures widely accepted in literature, representing how elements of the stack work, which at last is the ultimate role of viewpoints (Walewski & Heiles, 2016). The RMI4.0 (Figure 3.13) and its functional view are here introduced (Figure 3.14) for a better comprehension of design descriptions.

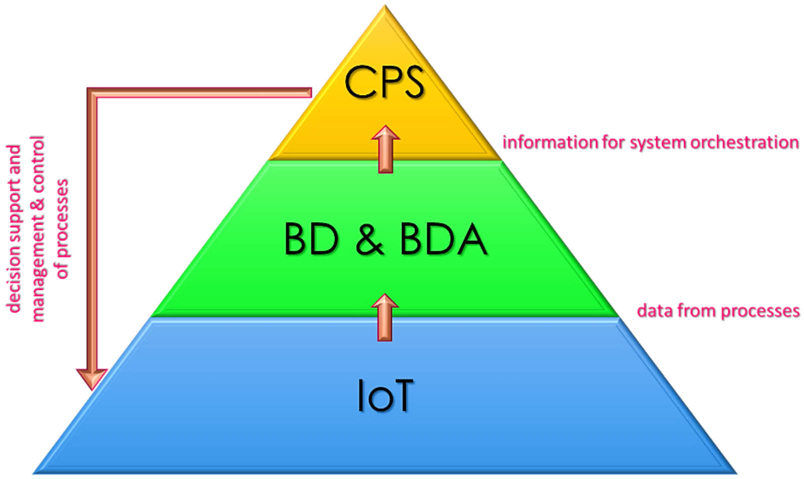

Figure 3.13. The RMI4.0

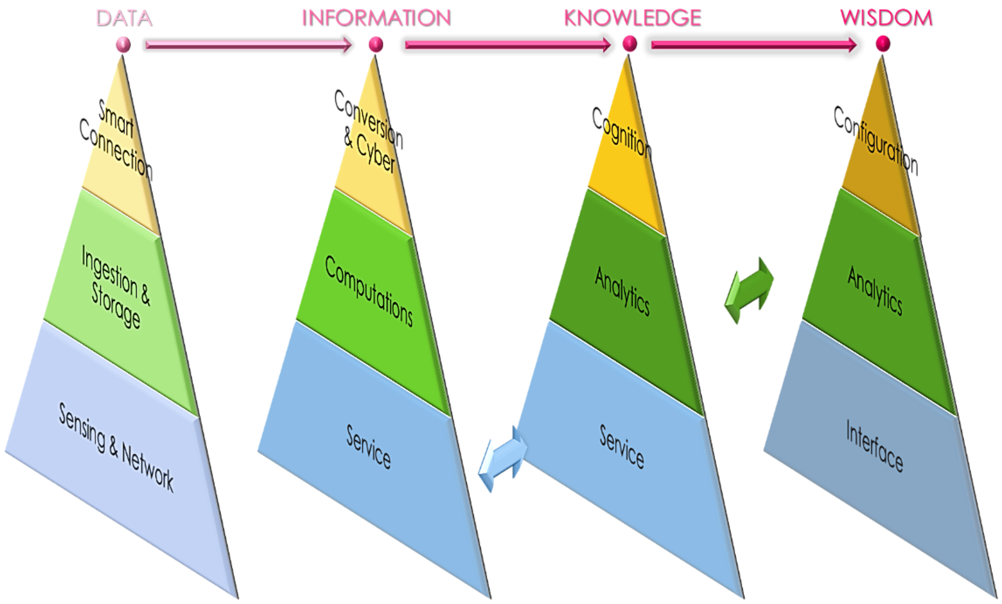

Figure 3.14. Functional view of RMI4.0

Descriptions of RMI4.0 and its functional view follow in the rest of the section, then graphics are commented.

3.3.1 The technology stacks

Initially aimed to provide fine-grained information enabling company management to measure, plan and act accordingly, IoT widened its application into all-day life (Uckelmann et al., 2011). The further step of evolution from connectivity for anyone forward to connectivity for anything[62], initially with focus on digital identification and M2M (Atzori, Iera, & Morabito, 2010), can be considered the seed of I4.0 as the focus moved from humans communicating with humans, to eventually machines interacting with machines (Weyrich & Ebert, 2015). The connectivity for anything has been possible by adding IoT technologies to already heavily automated manufacturing processes, with the consequent opportunities and challenges, of course (Shrouf et al., 2014). The further stress on connectivity for anything and communications of assets has eventually developed into the raising of the CPS. In fact, IoT can be defined as a network in which CPS access to cooperate with each other by unique addressing frameworks, integrating (i) physical assets and processes with computation capacities exploiting embedded SMs and computers, as well as (ii) assets and humans capable of be integrated exploiting smart devices and suitable technologies (Kagermann et al., 2013; Nolin & Olson, 2016; Pisching et al., 2018). CPSs and humans interact in a cooperative work environment by means of Artificial Intelligence, Virtual and Augmented Reality technologies, HMI, 'mobile devices', RFID, and more in general all the systems that allow to acquire data, and manage interconnected physical assets and computational capabilities (Aceto et al., 2019; J. Lee, Bagheri, et al., 2015). According to the lexicon of J. Lee et al. (2015) devices for acquiring data are here named 'sensors'. Sensors in addition to the 'network', which allows the interconnection of assets, constitute the CPS functionality, named by the J. Lee et al. (2015) 'connectivity'. Internet of course but also software and protocols and standards are the components useful to provide the system with the connectivity, as it comes from the work of Ungurean, Gaitan, and Gaitan (2014).

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[62] Source: The Internet of Things. Technical Report 27441, International Telecommunication Union, November 2005. Retrieved in (Aceto et al., 2019)

As a result of the evolution described so far, IoT devices continuously generate data, coming from products, processes, as well as direct inputs (Tu, Lim, & Yang, 2018). Two serial results have been then achieved. The former relates to the digitalization of processes, which leads to the digital transformation of systems (Bloomberg, 2018). Beyond the outcome of the 'digital transformation' of businesses, that Coreynen, Matthyssens, and Van Bockhaven (2017), and Gobble (2018) identify in its r/evolution towards servitization, a "*digital thread that links disparate systems across the product lifecycle and throughout the supply chain*" emerges (Hedberg, Feeney, Helu, & Camelio, 2017). This concept drives data-driven applications that can generate domain-specific knowledge for decision support, requirements management, and more in general management and control of manufacturing processes (Hedberg et al., 2017). This first result further enhance the availability of data since that exponential increase in volume and accessibility of data, their complexity, heterogeneity, high speed, and lack of structure, eventually introduce the BD paradigm (Marz & Warren, 2015). Alcácer and Cruz-Machado (2019) even argue that IoT without BD paradigm IoT is more dangerous that advantageous for business. The next result is that the BD utilization for decision making allows to integrate CPSs that have emerged as core technology to blend and coordinate resources producing data and elaborating information towards better orchestration of the system in which resources operate (J.-Y. Chen et al., 2017; Rajkumar, Lee, Sha, & Stankovic, 2010).

As a result, data are in the middle between the data acquisition and the data utilization. Data acquisition is possible via IoT, meant as both (i) complex of objects digitalizing all physical systems (Bortolini, Ferrari, Gamberi, Pilati, & Faccio, 2017), as well as (ii) the infrastructures which collect data and allows to enable CPSs (Oks & Fritzsche, 2015). BDA elaborates into information the large amount of data (i.e. BD) collected and provide them to CPS (J. Lee, Ardakani, Yang, & Bagheri, 2015), that utilize the information obtaining knowledge of the system towards a kind of system self-regulation (J. Lee, Bagheri, et al., 2015). Which sounds as closing the gap between the knowledge of the system and its wisdom within the Data-Information-Knowledge-Wisdom model (Ackoff, 1989) which is the information standpoint towards which I4.0 business have to point (Ardito, Petruzzelli, Panniello, & Garavelli, 2019).

3.3.2 Functional view of stack components

The view of the stack IoT-BD-CPS that this thesis wants to represent is that related to the smartification of the systems towards the realization of the SF. This view leverages some instrument:

- The 'IoT architecture' (L. Da Xu et al., 2014). This architecture is composed of four layers:
    - the 'Sensing Layer' to percept the status of objects and systems and uniquely integrate them, via actuators, sensors, RFID tags and other devices capable of acquire data (e.g. PLC)
    - the 'Network Layer' that transfers data captured via 'Sensor Layer' through wired or wireless network to the next 'Service Layer', mapping and connecting objects and enabling their capability of sharing data
    - the 'Service Layer' that makes use of technologies (i) supporting services and applications (e.g. data storage, exchanging and management of data) required by the users or applications (e.g. middleware, platforms), and (ii) routing the interoperability among heterogenous devices
    - the 'Interface Layer' that allows to interconnect and manage objects easily, and to display information in a clear and comprehensible way for interaction of the user (both machines and humans) with the system.

- The 'Big Data framework classification'. This classification is provided by Al-Gumaei et al. (2019) who have analyzed four frameworks for BD, i.e. the 'Big Data Taxonomy'[63], the approach of Ellingwood (2016), and the 'Big Data Landscape'[64]:
  1. 'Data ingestion frameworks', which deal with transferring raw data from data sources to the big data system and handle format and integration issues
  2. 'Data storage frameworks', which include distributed file systems and databases that persistently store varieties of big data formats
  3. 'Computation frameworks', which are capable of (i) processing large datasets and (ii) concurrently routing their elaborations to machines. Elaborations relate to both batch processing of blocks of data and stream processing of continuously processed data
  4. 'Analytics frameworks', which consists of algorithms and computations used (i) to unlock value from big data and (ii) to make predictions about future trends based on past events
- The '5C architecture' of Lee et al. (2015). It is an extension of the '3C architecture', namely 'Computation' 'Communication'-and 'Control' (Ahmadi et al., 2018; Hu et al., 2012). The architecture is composed by five hierarchical functions each one characterized by some attributes of CPSs corresponding to specific technologies to adopt for realizing them:
  1. 'Smart Connection': is the bottom hierarchical level characterized by the data acquisition through sensor network, controllers, as well as enterprise manufacturing systems. It requires standards and protocols since the variety of data. It relates to the system condition monitoring
  2. 'Conversion': is the hierarchical level dealing with transforming data into information. It consists of suitable algorithms, and relates to system self-awareness
  3. 'Cyber': is the middle layer acting as a central hub, which routes information to every connected system, forming the system network. Digital twining and Analytics (e.g. data mining) are needed for elaboration and synthesis of information gathered. This layer enables the CPSs and allows them to self-comparisons
  4. 'Cognition': this layer deals with providing users with the proper knowledge about the system acquired, for prioritizing and optimizing decisions
  5. 'Configuration': this layer realizes the feedback from the cyber space to physical space, and make machines self-configure and self-adaptive
- The 'Wisdom hierarchy' (Rowley, 2007). Rowley (2007) 'Data-Information-Knowledge-Wisdom (DIKW) hierarchy' (Ackoff, 1989) considering the source specificity of each hierarchy item, and then has made it into the 'Wisdom hierarchy' by mapping the 'DIKW hierarchy' onto several notable information system hierarchies. Author (Rowley, 2007) refers the D-I-K-W hierarchy to the 'Transaction Processing System'-'Management Information System'-Decision Support System'-'Expert System' hierarchy of derived information system. The information system hierarchy built by Rowley (2007) is described by ISA 95 automation pyramid[65] and its characterization through communication networks (Ikram & Thornhill, 2010; Tountopoulos et al., 2018).
  - The 'Transaction Processing System' refer to the 'Production Processes' ISA 95 level. It operates within the 'Field Network' in which data are collected from processes running

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[63] "Big data taxonomy", October 2014. Retrieved in Al-Gumaei et al. (2019). Not founded on the web.

[64] Source: Big data landscape 2018. Available from: http://www.qaware.de/fileadmin/user_upload/QAware-Big-Data-Landscape-2018.pdf. Last access: 2020.09.18

[65] Retrieved in Åkerman (2018)

  through sensors, devices producing signals (e.g. RFID), and other field devices, within both wired and wireless networks, and also using 'Collection' and 'Management' functionality of the Cloud which refers to capturing and aggregation of data, and storage-preservation-access functionalities
  - The 'Management Information System' refers to the 'Sensing & Manipulating' and 'Monitoring & Supervising' ISA 95 level. It realizes control and processing of operations exploiting PLC, SCADA, HMI, and 'Preparation' functionalities of the Cloud, namely pre-processing of raw data collected at the previous hierarchy layer
  - The 'Decision Support System' refers to the 'Manufacturing Operations Management' ISA 95 level. It exploits MES for operations management and relates to 'Processing' functionality of the Cloud, which uses data analytics, simulation, modelling and related technologies for providing management and operations decision maker with suitable instruments
  - The 'Expert System System' refers to the 'Business Planning and Logistics' level of the ISA 95 pyramid, which leverages ERP systems and Cloud 'Distribution' functionality for visualization and representation of the system state addressing business decision-making processes

Then, it is used for linking the 'Wisdom hierarchy' and other architectures and frameworks of I4.0. The full combination of structures is provided in the bullet list below. DIKW meanings are provided by Ackoff' definitions (1989) (in italic font), and then are mapped to types of information systems as made by Rowley (2007). The meaning of each element towards I4.0 technology stack is provided from the original works considered:

- "*Data are defined as symbols that represent properties of objects, events and their environment. They are the products of observation. But are of no use until they are in a useable (i.e. relevant) form. The difference between data and information is functional, not structural*". Data in the information system hierarchy of Rowley (2007) are contained in the 'Transaction Processing System'. They are acquired at the 'Sensing layer' of IoT by means of sensor belonging to the bottom function 'Smart Connection' of CPS, and then are transferred to the 'Network layer' of IoT for 'Data ingestion' and 'Data storage' within BD frameworks.
- "*Information is contained in descriptions, answers to questions that begin with such words as who, what, when and how many. Information systems generate, store, retrieve and process data. Information is inferred from data*" within the middle architecture functions 'Conversion' and 'Cyber', since the relationship with the 'Management Information Systems' level of Rowley (2007). 'Conversion and Cyber functionalities' are realized by means of 'Service layer' and 'Computation frameworks' of IoT and BD respectively.
- "*Knowledge is know-how and is what makes possible the transformation of information into instructions. Knowledge can be obtained either by transmission from another who has it, by instruction, or by extracting it from experience*". In the derived information system hierarchy (Rowley, 2007), it matches to the 'Decision Support System', which in the 5C architecture of CPS is related to the high function 'Cognition' realized through 'Analytics framework' of BD still within the 'Service layer' of IoT architecture.
- Finally, Intelligence and Wisdom belonging to the 'Expert System' of information system (Rowley, 2007) are reached, and they refer to the ability of increasing efficiency and effectiveness. "*Wisdom adds value, which requires the mental function that we call judgement. The ethical and aesthetic values that this implies are inherent to the actor and are unique and personal*". It matches the higher CPS function 'Configuration' realized through 'Interface layer' of IoT by means of 'Analytics frameworks'.

Table 3.3 recaps how DIKW hierarchy and architecture of I4.0 are interconnected for achieving wisdom within SFs of I4.0.

Table 3.3 - Mapping I4.0 architecture onto DIKW hierarchy, towards system smartification

DIKW hierarchy	**Information system hierarchy level (Rowley, 2007)**	**ISA 95 pyramid; network and technologies; Cloud functionalities**	**IoT layers** (S. Li, Da Xu, & Zhao, 2015)	**BD frameworks (Al-Gumaei et al., 2019)**	**CPS functionality** (J. Lee, Bagheri, et al., 2015)
Data	*Transaction Processing System*	*Production Processes; Field network and field devices (generally sensors); Collection and Management*	*Sensing Network*	*Data ingestion* *Data storage*	*Smart Connection*
Information	*Management Information System*	*Sensing & Manipulating and Monitoring & Supervising; Control and Operations network via PLC, SCADA, HMI; Preparation*	*Service*	*Computation*	*Conversion* *Cyber*
Knowledge	*Decision Support System*	*Manufacturing Operation Management; Management network and MES; Processing*		*Analytics*	*Cognition*
Wisdom	*Expert System*	*Business; Business Planning and Logistics via ERP; Distribution*	*Interface*		*Configuration*

3.3.3 The RMI4.0

As a result of the previous analysis, the RMI4.0 can be designed, and its functional view provided.

The RM is designed as a hierarchical stack in which IoT is the backbone, BD are produced by IoT and BDA addresses the functionalities of CPS. In this thesis, an approach in which the RM is designed as a pyramid is adopted. The bottom level is represented by the IoT, the peak is represented by the CPS. In the middle BD are generated by IoT and BDA route information to CPS. Edges of each pyramid sector are permeable to feed forward flows of data and information. Feedbacks from CPS functionality are sent to IoT layer for orchestrating systems via decision support and management & control of processes. This is conceived to realize the wisdom view of the SF. Feed forward transfers and feedbacks are represented in Figure 3.13 with red-colored arrows.

The functional view of RMI40 describing its functionalities, namely as components work together, directly comes from the view of the technology stack discussed in previous subsection. Views replies the hierarchical levels of the technology stack, and each layer belong to suitable classification of relative noteworthy architectures. The lower level of the pyramid slices relates to data acquisition from objects and data transfer to systems capable of processing them. The next level relates to processing of data for transforming into information useful for acquiring knowledge of the system in the upper level. Finally, at the top reside functionalities related to the information routing to suitable machines and devices that accordingly interact and behave.

For validating the RMI4.0 two applications are tested. They entail mapping RAMI 4.0 and the 65 RAs analyzed in the review of literature onto RMI4.0 for practically verifying weather it can support the designing of RAs.

RAMI 4.0 and RMI4.0

The RAMI 4.0 realizes different viewpoints (Kannengiesser & Müller, 2018) through the IT representation layers (i.e. the vertical axis), namely the 'Production Control', 'Business Processes', and 'Integration' viewpoints. These viewpoints are expressed by meeting or not specific layers of (i) product life cycle (i.e. right-hand horizontal axis) and (ii) hierarchy levels of system functionalities axes (i.e. left-hand horizontal axis). Integration and Communication layers express the 'Integration' viewpoint; Information, Functional, and Business layers realizes the 'Production Control' and 'Business Processes' depending on what system hierarchy and product life cycle levels they meet. As a result, it is useful mapping RMI4.0 onto IT representations layers to surely meets its all layers and levels.

A characterization of IT representations layers comes from (Ye & Hong, 2018). Authors relates the 'Asset' layer to the real world of field devices and objects (e.g. machines, robots, sensors, actuators, controllers, RFID). 'Communication' and 'Information' layers deal with elaborating the digitalized real world, providing communication and information services respectively, namely data transport (e.g. fieldbus protocols, AutomationML, MQTT, OPC UA, Edge network) and data management (e.g. Systems Modelling Language, Cloud, Machine Learning, process modelling, Edge/Fog computing, accordingly. 'Integration' layer is in the middle between 'Asset' layer, and 'Communication' and 'Information' layers, digitalizing the real world and providing the digitalization to the cyber world. 'Function' and 'Business' layers realizes domain specific applications for the enterprise process-control system (e.g. knowledge management, platform applications, service applications, control strategy, APIs, HMIs, SOA-based resources).

Moreover, according to characterization of I4.0 components in Pisching et al. (2018), CPS realizes the functionalities of 'Function' and 'Business' layers, whereas IoT realizes the 'Asset', 'Integration', 'Communication', and partially 'Information' layers functionalities.

As a consequence, RAMI 4.0 can be mapped onto RMI4.0 as in Table 3.4.

Similarly, deriving from the relation among IT layers and the I4.0 components, it is possible to verify how well RMI4.0 represent and I4.0 component. According to characterization in Contreras, Garcia, and Diaz (2017), and (Ye & Hong, 2018) the 'Asset' layer represents the physical 'Things'. 'Information', 'Functional', and 'Business' layers are contained in the 'Administration Shell'. The 'Integration layer' provide the virtual representation of objects (transformation and transportation via OPC UA standard into the cyber world), and 'Communication layer' deals with connection among cyber objects. Thus, also RMI4.0 realizes the I4.0 as in Table 3.5.

Table 3.4 - Mapping RAMI 4.0 onto RMI4.0

RAMI 4.0	**RMI4.0**
Asset layer	*IoT LEVEL*
Integration layer	*IoT LEVEL*
Communication layer	*IoT LEVEL*
Information layer	*IoT and BD & BDA LEVEL*
Function layer	*CPS LAYER*
Business layer	*CPS LAYER*

Table 3.5 - Mapping I4.0 component onto RMI4.0 by means of RAMI 4.0

RAMI I4.0 y-axis layer	RAMI I4.0 component	RMI4.0
Business	Administration Shell	*IoT LEVEL*
Functional	Administration Shell	*IoT LEVEL*
Information	Administration Shell	*IoT LEVEL*
Communication	Communication (via OPC UA)	*IoT and BD & BDA LEVEL*
Integration		*CPS LAYER*
Asset	Thing	*CPS LAYER*

The same process has been successfully realized for all 65 RAs retrieved in literature, adopting the RAMI 4.0 as ‘translator’ from original RAs and the RMI4.0. Results are provided in Appendix 3-B to this chapter.

3.3.4 Discussion on RMI4.0 and results of application

In this chapter an I4.0 RM for SMEs has been provided, namely the RMI4.0. The acronym RMI4.0 sounds as a license plate, and actually it wants to enable the SMEs to drive I4.0 VN. A RM has been preferred to other system architecture models since its higher level of abstraction, that better meets the requirements of a ‘blueprint’ for the SMEs, namely its simplicity and actual realizability. The model design has followed a specific literature thread from which the relation of its component (i.e. IoT, BD & BDA, and CPS) has been derived. Of course, other threads do exist, for instance in which IoT and CPS are somehow alternatives for IMS. However, the literature thread focused has been followed coherently along all the designing stages.

RMI4.0 pursues three fundamental purpose for dissemination of I4.0 architectures within SME environments. First, it is provided in its technical viewpoint, for providing SME managers with the technology stack to implement. Second, it is simple and clear for letting SME management understanding how it is possible to realize RAs and architectures properly for their own business purpose and structures. Third, it copes with interoperability, for practical implementation. First result has been achieved by using the technology elements identified for promoting SF of I4.0 (as derived in Chapter 2). The second result has been achieved deciding to design a RM instead of a RA for introducing the concept of RA within SMEs with a higher level of abstraction, which is supposed to foster the digestion of I4.0 meanings. Third result has been achieved validating the possibility of design RAs starting from RMI4.0 by using it for successfully describing RAMI 4.0 and other I4.0 relevant models, RAs, and architectures of systems engineering.

Furthermore, for helping SMEs in understanding I4.0 systems, an approach in which it is related to traditional information systems hierarchy and automation pyramid has been followed, since these frameworks are reliable and well-understood in SMEs adopting them for a long time. Although it is generally accepted that hierarchies and vertical structures develop into network in I4.0 systems, this aspect has been judged useful for fostering I4.0 dissemination among SMEs, and thus it has been adopted consciously since a RM is just an abstract copy of the practical realization for a high-level description of how the system work, and thus do not bias an actual implementation of a system coherent with all I4.0 principles.

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Appendix 3-A

Table 3.6 provides the individual characterization of studies on RAs as they can be mapped onto RAMI 4.0. For space constraints and the sake of readability of the table, studies are labeled by an ID. The correspondence among IDs and studies is provided in Table 3.7.

Table 3.6 - Mapping 65 RAs retrieved from literature review onto RAMI 4.0. Empty rows stand for 'data not enough to map the RA onto RAMI 4.0'

Study ID	**y - functionality of the component**	**y - functionality of the component x - product lifecycle**	**z - aspects of industrial branches**	**z - aspects of industrial branches x - product lifecycle**	**z - aspects of industrial branches y - functionality of the component**	**z - aspects of industrial branches y - functionality of the component x - product lifecycle**
1						1
5			1			
6.1					1	
6.2			1			
6.3						
6.4						1
7.1				1		
12					1	
13						1
14.1					1	
18					1	
19.1	1					
20						1
21			1			
21.2			1			
21.3					1	
22					1	
23.2			1			

23.3	1					
24			1			
25				1		
28	1					
34					1	
36						1
38			1			
40	1					
40.2						1
41						1
42					1	
43			1			
45			1			
46			1			
47						
48				1		
51			1			
52						
53.1			1			
54			1			
55			1			
56.1			1			
56.2			1			
56.3			1			
56.4			1			
56.5			1			
59			1			
61.1			1			
61.2		1				
63					1	

67.1			1			
76						1
77			1			
84	1					
92			1			
93			1			
105.1						1
113			1			
122		1				
123					1	
126					1	
126.1					1	
127					1	
128			1			
133			1			
134						
Total	**5**	**2**	**27**	**3**	**11**	**9**

Table 3.7 - References for study IDs used in Table 3.6

Study ID	Reference
1	(Yi Liu et al., 2019)
5	(Sarabia-Jácome et al., 2019)
6.1	FAR-EDGE Project: FAR-EDGE Project H2020 (2017). Source: http://far-edge.eu/#/. Not available on the web
6.2	Edge Computing Consortium, Alliance of Industrial Internet: Edge Computing Reference Architecture 2.0. Technical report, Edge Computing Consortium (2017). Visit: http://en.ecconsortium.net/Uploads/file/20180328/1522232376480704.pdf. Last access: 2020.10.19
6.3	(M. Tseng et al., 2018)
6.4	(Lin, Miller, et al., 2017)
7.1	Valckenaers, P. (2018, June). ARTI reference architecture–PROSA revisited. In International Workshop on Service Orientation in Holonic and Multi-Agent Manufacturing (pp. 1-19). Springer, Cham.
12	(Maple et al., 2019)

13	(Larrinaga et al., 2019)
14.1	ISO/IEC, 2018. Internet of Things (IoT)—Reference Architecture. ISO/IEC 30141:2018. National Standards of America. Retrieved in Yuan, Chen, Xu, and Chen (2019)
18	(Helo & Hao, 2019)
19.1	(J. Lee, Bagheri, et al., 2015)
20	(Yli-Ojanperä et al., 2019)
21	(Al-Gumaei et al., 2019)
21.2	(Yamato et al., 2016)
21.3	(Wan et al., 2017)
22	(Wu et al., 2019)
23.2	OpenFog Reference Architecture. Visit: https://www.iiconsortium.org/pdf/OpenFog_Reference_Architecture_2_09_17.pdf. Last access: 2020.09.18
23.3	Web of Things Architecture. Visit: https://www.w3.org/TR/wot-architecture/#introduction. Last access: 2020.09.19
24	(Jiang et al., 2019)
25	(Neal et al., 2019)
28	(Kang et al., 2019)
34	(Koziolek et al., 2019)
36	(Corradi et al., 2018)
38	(Yoon et al., 2019)
40	(Redelinghuys et al., 2019)
40.2	Manufacturing Industry Digital Innovation Hubs (MIDIH) Reference Architecture (2018). Visit: https://midih.eu/documents/MIDIH%20Reference%20architecture.pdf. Last access: 2020.09.19
41	(Cupek et al., 2019)
42	(Trabesinger et al., 2019)
43	(Oks et al., 2019)
45	(Qi & Tao, 2019)
46	(Landolfi et al., 2019)
47	(Kosak et al., 2019)
48	(Montavon et al., 2019)
50	(Yasmin et al., 2018)
51	(Buenabad-Chavez et al., 2018)
52	(Tountopoulos et al., 2018)
53.1	(Bassi et al., 2013)

54	(Vucnik et al., 2018)
55	(Balogh et al., 2018)
56.1	(Bandyopadhyay & Sen, 2011)
56.2	(L. Da Xu et al., 2014)
56.3	IoTWF (2014). The internet of things reference model. CISCO in Internet of Things World Forum. Visit: http://cdn.iotwf.com/resources/71/IoT_Reference_Model_White_Paper_June_4_2014.pdf. Last access: 2020.09.19
56.4	(Martin Bauer et al., 2013)
56.5	(M. Bauer et al., 2013)
59	(Ye & Hong, 2018)
61.1	IBM, "Industrie 4.0 Architecture," 2018. Retrieved in Moghaddam, Cadavid, Kenley, and Deshmukh (2018)
61.2	(Yan Lu et al., 2016)
63	(Pedone & Mezgár, 2018)
67.1	(Hermann et al., 2016)
76	(Illa & Padhi, 2018)
77	(Erasmus et al., 2018)
84	(Chakravorti et al., 2018)
92	(Helu et al., 2017)
93	(Montavon et al., 2017)
105.1	(Gröger et al., 2016)
113	(Westermann et al., 2016)
122	(Yoon & Suh, 2016)
123	(O'Donovan et al., 2016)
126	(Bordel Sánchez et al., 2015)
126.1	National Insitute of Standards and Technology (NIST). Retrieved in Bordel Sánchez et al. (2015)
127	(Sayed et al., 2015)
128	(Kassner et al., 2015)
133	(Stoyanov & Rusev, 2019)
134	(B. Chen et al., 2017)

Appendix 3-B

Table 3.8 maps 65 RAs retrieved in literature and qualitatively described onto the RMI4.0. RAs are mapped according to their 'vertical development', namely from the lower layers that are related to the IoT layer, to the higher that are related to the CPS layer. Resources expresses the frameworks and the hierarchical relation among elements, whereas attributes represent the component and sources used for realizing the architecture layer. Lexicon used is adopted from the authors who have designed the RAs, refer to the original work for the full explanation. Convention adopted for representing the relation among components is the following:

- Symbol '-' means a next upper level/layer of the original architecture
- Symbol '|' means an intermediate layer among two successive level/layer of the original architecture
- Symbol ';' means a next close component on the same level/layer of the original architecture

References for study IDs are provided in Table 3.7.

Table 3.8 - Mapping 65 RAs retrieved from literature review onto RMI4.0

ID	IoT lower layer	IoT resources	IoT attributes	BD middle layer	BD resources	BD attributes	CPS higher level	CPS resources	CPS attributes
1	Smart Factory architecture based on the Internet of Things	Devices - Protocols - Gateway - Cloud Backend	assets - es. Zigbee, Modbus - JSON, REST API, websocket, Java-based middleware - IoT application platform	Industrial Big Data Cloud Platform	Data Source Layer - Data Loading Layer - Data Service/Storage Layer - Application Layer	unstructured/structured data - data acquisition, cleaning, conversion | sensor interface | Clustering | paltform interface | Monitoring, Analysis, Web Service	5C architecture of CPS (Bagheri, B., Yang, S., Kao, H. A., & Lee, J. (2015). Cyber-physical systems architecture for self-aware machines in industry 4.0 environment. IFAC-PapersOnLine, 48(3), 1622-1627.)	Connection - Conversion - Cyber - Cognition - Configure	Condition Monitoring - Self-Aware - Self-Compare - Prioritize and Optimization Decisions - Actions to Avoid
5				BD architecture	IDS Connector - Data Integration - Repository and Processing - Visualization	Automatic Identification System (AIS), NGSI - NiFi, kafka - Hadoop, Spark - Application Web		IDS connector	Fiware IoT platform
6.1		edge network					Physical World - Edge Services - Cyber World	assets - edge network - Enterprise and Control Applications	IoT - Cloud, Edge/Fog Computing - Cloud, Distributed Analytics and Services
6.2	Connectivity and Computing Fabric	Edge Computing Network - smart asset, smart gateway, smart system	Operation, Information and Communications Technology (OICT)	Full-lifecycle data service of the Service Fabric	Data Processing - Data Analysis - Data distribution and policy execution - Visualization and storage	Filter, Aggregation, Semantic parsing - Statistics, Model processing, Complex Event handling - Policy execution for distribution - display modes	Smart Service	Development service framework - Deployment & operation service framework	Develop, Integrate, Verify, Release - Service Orchestration, Application deployment, Application market

6.3	Edge Device - Edge Tier	Compute - Data storage and Connectivity		Platform Tier - Enterprise Tier	Data store - Compute	Applications, Analytics, Dashboards	IIC Crosscutting Functions	Distributed Data Management, Industrial Analytics, Global Orchestration, Connectivity, Security	
6.4	implementation viewpoint	Edge Tier	Industrial Internet Connectivity Framework (IICF) - extended the IIRA to IIoT connectivity	Implementation Viewpoint	Platform Tier - Enterprise Tier	Access Network | Service Platform | Service Network | Domain Applications (rules & control)	Functional viewpoint	Physical System - Control - Operation, Information, Application - Business	
7.1				Intelligent Being - Intelligent Agent			Type - Instance | Resource - Activity		
12	CAV - D&P - E&I	Actuators, Sensors (CAV) - Sensors (D&P) - Sensors (E&I), Edge	Wireless Connections - WiFi/Cellular	CAV - D&P - E&I	Physical I/O, Data Storage (CAV) - Applications (P&D) - Edge , Cloud (E&I)		CAV - D&P - E&I		
13	Edge tier	Physical entity - Edge Gateway - Local Storage	asset (clutch brake in the case study) - FTP - cloud gateway	Platform tier	Orchestration system - Service registry - Authorization system	Edge broker - Processors	Enterprise tier		external stakeholders and systems
14.1	Physical Entity Domain | Sensing, Controlling, Communication unit | Logical control unit | Edge subsystem	Logical Control Unit | Edge subsystem	Operation&Management Domain - Application&Service Domain - Access&Communication Domain	User Domain		OMD - ASD - ACD			
18	IoT layer	RFID - GPS - Sensor - Barcode	Etherum Network	Data Layer	Quality Data - Logistics Data - Transaction Data	Transaction - Block - Blockchain	Business - User - Operation Layer	Client-Local Web Server-Local Database-Blockchain	Digital Identity, Smart Contract - Logistic Operator, Customer - Scheduling, Collection, Decision-Making
19.1	Smart-Connection Level	Plug&Play - Tether Free Communication - Sensor Network	Sensor Network	Data-To-Information Conversion Level - Cyber Level - Cognition Level	Smart analytics, Component machine health, Multi-dimensional data correlation, Degradation and performance prediction - Twin model for components and machines, Time machine for variation identification and memory, Clustering for similarity in data mining - Integrated simulation and synthesis, Remove visualization for human, Collaborative diagnostics and decision making	Data analytics, Predictive Maintenance - Digital Twin, Data mining - Collaborative Decision-Making	Configuration Level	Self-Configure resilience - Self-adjust for variation - Self-Optimize for disturbance	Smartification of assets
20	(RAMI 4.0) Communication layer		extended OPC UA				(RAMI 4.0) Business Layer - Type, Instances	Manufacturer - OEM	Manufacturer Type processes | OEM Type processes | OEM Instance processes

21	Asset Layer - Integration Layer - Communication Layer	Communication Protocols | Batch Data / Distributed Stream Platform	Device, Machine, Sensors | Legacy Field and Industrial Ethernet | PLC | Metadata Registry	Information - Functional	Distributed Data Storage Framework - Distributed Stream / Batch Processing Framework |Interactive Analysis, Dashboards	Stream data, Machine Learning (for Model Building - model in production)	Business Layer	Anomaly Detection, Energy Optimization, Condition Monitoring	Industrial Use Cases
21.2	Edge Network	Edge and Cloud	MQTT, HTTP - Sensors, Storage, DB	Batch Layer - Speed Layer	ERP - PSPP	learning model and sources			
21.3	Acquisition Layer - Data Transmission Layer	Data sources - Data transmission	Equipment, Workshop, Factory - Industrial switch, Wireless AP, Industrial routing	Big Data Analytics Platform	RT BDA platform - Offline BDA Platform	Cloud (Apache STORM) - Active Maintenance plans	Factory Layer	Visual surveillance - Maintenance	Facilities, Workshop, Factory - Cloud platform (batch processing)
22	CPS fractal structure	data protocol and service interface	Environment (sources) and Perception (collection) of the Data-driven operating mechanism: sources (services, production, database, fractals-connection) - RT collection of field data, batch collection of service data - IoT data gateway and router	CPS fractal structure	perception, analysis, decision, execution	Perception (pre-processing & storage) - Analysis - Decision & Execution of Data-Driven Operating Mechanism Architecture: data cleaning, edge computing, distributed storage - data management - data fusion, data mining, semantic processing - decision making-knowledge discovery-knowledge management, message routing-decision execution-accurate control	CFS implementation architecture	Physical mfg Resources - Fractal - Virtual Mfg System - Company fractal system - Mfg and Service activities	structural (structure) and functional (CPS) abstraction - encapsulation - mapping - implement, supply, customization
23.2		Sensors, Actuators, Control - Protocol abstraction Layer - Hardware Platform Infrastructure - Network, Accelerators, Compute, Storage			OpenFog Node security - OpenFog Node Management - Hardware Visualization - Node Management & Software Backplane		Application Support & Application Services		
23.3	Local Network Layer - Edge Layer	Direct Thing-to-Thing interaction - Complement Existing Devices | Integration & Orchestration	Thing, Thing+Consumer, Existing Device | Cintermediary / Thing	Cloud Layer & Edge Layer	Thing to Cloud - Remote Access and Synchronization - Thing to Gateway	Intermediary / Thing	Seamless Web Integration	Consumer	Thing of the Local Network
24	Resource Layer	Machine Tools, Cutting Tools, Conveyors, Robots, Staffs, RFID Devices, workpieces, Sensors and Controllers	| CAN, RS232, USB, WiFi, Fieldbus, Industrial Ethernet |	Dataspace Layer - Configuration Layer	Data and Knowledge scheme - Manufacturing Resources and Digital Twins models	Data sources and Communication Computing Control	Runtime Layer - Application Layer	Gantt Chart-driven runtime and evolution - Industrial Web Applications	H2M, M2M, M2H | micro-services and REST APIs | business practices (order management, process planning, condition monitoring, performance prediction, quality control)
25	Asset Layer - Integration Layer - Service Implementation Layer	Intelligent Container | WiFi | Service Bus	Users, Intelligent Component |Protocol Translation, Routing, Service Discovery Security, Network Integration	Service Abstraction Layer - Business Process Layer	Data Services - Information Handling	Batch data - RT information	Application Layer	RTI Monitoring & Control	RTI Information analysis
28	Manufacturing Data	Real Factory | Manufacturing Data Interface	Machine, Robot, Sensor | SCADA, OPC UA, MT Connect	Cyber Model	Core Logics of Data Processing	Mapping, Calibrating, Scaling	Production Plan - History Database	Cyber Model for Throughput Analysis | Throughput Simulation	Factory, Process, and Machines - Simulation, Scheduling, and Maintenance Palling

								Model Conversion | Throughput Analysis	
34	Distributed Control Systems DCS	Controller - Field Device (Sensors, Actuators) - Public Driver Repository	OPC UA Local Discovery Servers (LDS) - Ethernet - Internet				Engineering Server - Operation Server	Public Driver Repository	Device Management OPC UA LDS - Supervision OPC UA LDS
36	Software architecture	Assets - Kernel space, User space	Controller, Motors, Compressors. Sensors - Modbus - OS, Libraries	Server-side architecture	Machine Management - Database Management System - Machine Web interface - Cloud	Role Based Access Control (RBAC) - CRM/ERP integration - Business and Configuration analytics and management - REST API - Dashboards and Reporting	Software architecture	Supervisor - Unified Teorema Interface	System management, verification, configuration - HMI, Process management, Energy monitoring, Remote control
38	Shopfloor Service Layer	Product Agent - Resource Agent - Human Agent	Product - SF items - HMI	Management Service Layer	SMES - SMC - SECM - SMO	Production Management - Resource Management - History Management - Forecasting	Process Layer	Process Application	Product - Service - Resource Management
40	Physical Twin - Local Data Repositories - IoT Gateway	Smart Connection Level of CPS - Data-to-Information Conversion Level of CPS	OPC UA Server - IoT Gateway, GUI	Cloud-based Information Repositories	Cyber Level of CPS - Cognition Level of CPS	OPC UA, SQL	Emulation and Simulation	OPC UA, SQL	Cognition Level
40.2	Product in the Real World - Industrial Shop Floor - Industrial IoT	Assets - Processes, Planning, Enterprise software	RT Data processes (security, visualization, processing, services) - IoT Middleware (gateway - broker) | Data persistence middleware	Industrial Analytics		Batch Data processes (security, visualization, processing, services) - Analytics Middleware (Models - Bus)	Smart Factory/Smart Products Apps Ecosystem		Functional/Type-Instance
41								TMQ System - Information Server Production Unit - Material - Warehouse & Internal Logistics	B2MML - OPC UA/ISA95
42	Shop Floor	Assets - Connectivity Platform	lathe, work center, robot - KEPServerEX PTC	Office floor	MES	SoliDat	Office Floor	MES | ESB	Connectivity modul | T-System PWC | PLM, ERP
43	Physical Sphere - Cyber Sphere	HCI - Hardware | Network	HMI - Infrastructure, control unit, Sensor-actuator module, Process module - | Interface, Connector	Cyber sphere	Data - Software	Artificial Data generation, Database - Backend software, Frontend software	Scenario	Setting - User	Use case, method - Staff, stakeholder group
45	Edge computing - Control layer	assets | edge computing devices | edge computing platform	resources, sensors, actuators | gateway, PLC, Hub, Industrial PC | data upload and filtering, feedback control, real time analysis and data integration	Fog computing - Integration layer	Fog gateway | Fog computing platform	Fog network, Local Server (ERP, SCM, MES, CRM) - Fog computing and management node for applications (production scheduling, inventory management, etc)	Cloud - Manufacturing service layer	Data (from fog) | services |stakeholders	fog node | cloud platform | business partners
46	Stakeholders - Web portal - Business Layer	Stakeholders mediator - Gateway Orchestrator	applications - API	Tools Layer - Data Layer	calculation tools | Blockchain platform | Semantic infrastructure	Ecosystem Data Manager			

47				Task Layer - Ensemble Layer - Agent Layer - Semantic hardware Layer	synchronization - coordination - communication	ScORe task - ensemble program - agent program - capability	semantic hardware layer		hardware
48	Data Provision and Access Layer	Development Cycle, Production Cycle, User Cycle	PLM, CAD, FEM, ERP/SCM, MES, BDE, CRM, CAQ	Aggregation and Synchronization Laye - Multi-Modal Information Access	Development Cycle, Production Cycle, User Cycle	proprietary systems - Model Reduction for Data Integration, Cluster Algorithms for Data Model, Learning Algorithms for Data Storage and Caching, Meta Heuristics for Context-sensitive Processing	Decision Support Layer	Development Cycle, Production Cycle, User Cycle	Event-Driven Decisions, Autonomous Actions, Adaptive Processes
50	Physical Layer - Communication Layer	assets - standards and protocols	physical object | ZigBee, LoRaWAN, Bluetooth, SigFox | LTE, Ethernet, 5G	Data Storage Layer - Applications Layer	Cloud Server - Local Server (application oriented servers)		Applications Layer		Users
51	Physical Layer	Plan Floor ; Enterprise Information System	Sensors, actuators ; Manufacturing Information Systems, Connected Supply Chain Systems	Operational Layer - Virtualization Layer ; Decision Layer	Data collection framework ; Complex Event Processing ; Data Analytics - Cloud Controller ; Modelling, Simulation, Optimization		Operational Layer - Virtualization Layer - Visualization Layer	Cyber-Physical System - Cloud Controller - Cloud Board	CPS - Decision making system
52				Data Storage Layer - Service Logic Layer - Service Access Layer	access to data - handle decisions - handle event	knowledge base, decision support DB, DISRUPT events, user management - DSS manager, controller service manager, event details component, notification manager, status manufacturing component, data collection connector, user manager, data access component, CPS connector - DSS API, User Request API, event listener			
53.1									
54	Local Network	internet - UHF devices, UWB device, LPWA device, SRD device		Management Server (Continuous Integration system)	Repository, Infrastructure Management and build automation system		Device	target node, infrastructure node	
55	Machine Layer - Controllers Layer	Production Equipment - Sensors, Actuators, Adapters	e.g. SCADA, PLCs, MTConnect, AutomationML	Internal Data Layer - Shared Data Layer - Collaborative Services Layer	Pre-processing and Secure Sharing - Methodologies, Equipment Models & Event - Analysis & Prediction Services	e.g. Apache, MQTT, OPC-UA - PaaS, SaaS - SQL	Process Layer	Scheduling and Planning	ERP, Maintenance Planning & Scheduling rules
56.1	Edge-technology - data capturing	Edge Technology - Access Gateway | Internet|		Network - data utilization	Middleware		Network - data utilization	Application	
56.2	Sensing - Network			Service			Interface		

56.3	Physical Devices & Controllers - Connectivity	The EDGE-Things in IoT - Communication & Processing Units	Sensors, Devices, Machines - Edge Nodes of all type	Edge (Fog) Computing - Data accumulation - Data abstraction	Data Element Analysis & Transformation -Storage - Aggregation & Access	Data in motion	Application - The Center- Collaboration & Processes	Reporting, Analytics, Control - People & Business Processes	Data at Rest
56.4	Device - Communication - IoT Service			Virtual Entity - IoT Process Management - Service Organization			Application		
56.5	Device - Communication - IoT Service			Virtual Entity - IoT Process Management - Service Organization			Application		
59	Asset - Integration - Communication	Field - Communication	sensors, actuators, controllers (e.g. robot, PLC) - data transport mechanism (e.g. fieldbus, protocols, MQTT, OPC-UA)	Information	Information	data management mechanism (e.g. STEP, SysML, AML)	Function - Business	Enterprise	domain specific application (e.g. control strategy, API, HMIs)
61.1	Equipment/device layer	edge networking	smart sensors and tools	Platform/hybrid cloud layer	Plant layer	device management, configuration management, security, visualization, development support, management, and cognitive service	Enterprise layer	Plant layer	plant orchestration
61.2	OT domain	functions provided by I4.0 components	assets	Virtual domain	queries and simulation services	digital factory or digital twin of the enterprise	IT and Management domain	services provided by the enterprise IT and all other services required by the enterprise	enterprise management
63	On-premises	Asset Instance - Communication - Information and Data - Functions Management in AR - I4.0 Standardization | OPC-UA	assets, task dispatcher, process planning & control, internet | OPC.tcp, http	Private Cloud	Database, Interface, Orchestration, Services, Direction	MES	Public Cloud	Scheduling, CP validator, Simulation, Dashboard, Data Analytics	
67.1	System Layer - Information Layer	execution and configuration - Information Model	technologies connected via connectors - vocabulary, information model	Process Layer - Functional Layer	Data Apps - Functional requirements	Data - connectors, vocabulary, metadata, apps, identity management, trust and security entities	Business Layer	Core participants, Intermediaries, Software and Services, and Governance Body	participants and activities
76	IT architecture - IoT architecture	Enterprise Applications (IT) - Manufacturing Applications | IoT Devices | IoT Platform	ERP, PLM, SCM, M2M, CRM - MES, OPC, PLC | Actuators, Machine Logs, Controllers, Sensors | IoT Gateway, Edge Computing, Data Integration (via Data Enhancement Layers)	Big Data Architecture	Data Platform | Data Visualization	Data Storage - Data Processing - Stream Processing - Predictions | BPM - API (Gateway & Management) - Mobile Apps, Web Portals, Data Analytics & Data Mining - Dashboards/Report - Monitor/Control			

77	On-device | Local Area Network | On-premises | Internet | On-cloud	Thing/device, software | LAN | Thing/device, communication and management | Internet | Application platform - Process Management & Analytics abd data management - IoT application	Human interface software, Sensor controller, Robot controller, Augmented reality software | LAN | HORSE local Execution | Internet | Open Source platform - HORSE Execution and Awareness - HORSE System						
84	Assets | Middleware	Standard PLCs, Manufacturing Cell (Robots, Machining), Robots, HMI | PERFoRM middleware		Middleware | Analytics	PERFoRM middleware | Simulation, Data Analytics, Storage		Enterprise IT	ERP, MES, SCADA, Storage	
92	Industrial Equipment Network // 1-Data and 2-Aggregation tiers	Physical Devices - Data aggregation/Contextualization - "Kill Switch" // Databases, Data objects, storage devices and Linked data, Application Server		Private Internet Network // 3-Delivery	Data Collection, Persistence, Contextualization // Cached Data, Web Servers	Volatile Data Stream, Query-able Database Repository, Data Packages	Public Internet //	Data Collection, Persistence, Contextualization // Thick Clients, Thin Clients	Volatile Data Stream, Query-able Database Repository, Data Packages
93	Device Layer		aggregated individual instrument interfaces	Management Layer		necessary information for processing data	Interaction Layer		processing data from the managment layer
105.1	Product Lifecycle - Value-added Middleware	Engineering, Production Planning, Manufacturing, Usage and Support - Integration Middleware	PDM, ERP, MES, CRM - PLM Bus, SOA Governance Repository	Value-adding Middleware	Analytics Middleware, Mobile Middleware	Manufacturing Knowledge Repository - Information Mining - KPI Management - Visual Analytics, Mobile Data handling and synchronization - Mobile Visualization	Role-based application (Value added Services)	Service Composition & Access	App Composer, App Marketplace
113	Subsystem	Basic System - Actuatory, Sensory	Environment	Information Processing	Communication Systems, HMI	Data, Human	Services	Networked Systems	
122	Smart Shop Floor - Smart MES - Smart Factory Service	Type, Factory Things, IIoT | Support Technologies | FIL Control - Cloud Service Bus	Product Industry-Factory, Process Industry-Plant (Man, Machine, Material, Environment, Method + RFID/RTLS, Wearables, Gateway HUB, MT_Connect, OPC-UA, AutomationML, Smart Sensors, Smart Device, Beacon) - Real Time Network Shopfloor | Data Analytics, CPS, Modular Factory, Eco Factory, Agent Based, System Optimization, Standardization | MES Backbone (Legacy Function, Integrated Monitoring, Integrated Analysis, Integrated Prediction, Shop Floor Optimization, Near R/T Simulation, Reconfiguration, Execution) - Smart Factory Service Network-Office Floor (Interface Mngmt, Data flow mangmt, Service orchestration, User authorization, UDDI, Data Encryption)	Smart Factory Service	Service Items	Predictive Maintenance, Integrated Energy Management, Connected Smart Factory, Global Monitoring & Diagnostic, Shop Floor Performance Indicator, 3D Printer Mock-Up, Urban Factory, Worker Safety, AR-based Training & Maintenance, Cloud Service for CAx	Systems Engineering for adoption	Systems Engineering for adoption	Smart Factory Adoption Engineering

123	Operational Technology - Information Technology	Batch Stream = Energy Management System, Building Management System, Maintenance Management System // RT Stream = PLC- Data Lake	SQL, MySQL ; Workflow Engine	Data Analytics	Other IDE, R OCOnsole, SAS	Explore & Model, Train Model, Standardize	Embedded Analytics	Embedded Analytics Application - Scoring Model	
126	Physical Systems - Cybernetic Devices - Monitor and Control System(s)	Timing, Inter-system services (REST interfaces)	TCP/IP, P/S, RFID/BLE	Data Analytics - Decision Making	Interoperability, Security, Data and Data service	REST services and XML	Business and User Goals	Human-System Interaction	
126.1	Physical Systems - Sensors and actuators - Monitor and Control System(s)	Timing, Networking and Communication		Data Analytics - Modelling, Optimization and Simulation	Interoperability, Security, Data and Data service		Business and User Goals	Human-System Interaction	
127	Control Layer - Data Layer	Sensor Node - SelSus HMI	Smart Device	Information Layer - Knowledge Layer	Sensor Node - SelSus HMI	Smart Device	System Level		
128	Integrate	Data Sources - Holistic Knowledge Repository	Unstructured ETL, Structured ETL	Analyze	Core Analytics - Value-Added Analytics	Text Analysis, Classical Analysis (Data Mining) - Root Cause Analysis, Correlation, Gap Analysis	Present	User Interface	Plug-and-Play analytics component, mobile/desktop
133	ViPS Physical World | Guards	IoT Node		ViPS Middleware	Event Engine | Digital Livraries Subspace, Operative Assistants, Analytical Subspace, Personal Assistants		ViPS User Interface	Web Applications	
134	Physical Resource Layer - Network Layer	Industrial Internet of Things	RFID, Sensor, PLC, Smart Meter, ZigBee | CAN, FF, HART, WIA-AP, IS A100.11a | Fog Node	Cloud Application Layer	Cloud Manufacturing stack | Service Application Interface	Server, Data Centre	Terminal Layer	Internet of Services	Decision makers, Implementers, Maintainers, User Experience

4 The Industry 4.0 Readiness of SMEs

As assessed by Schumacher et al. (2016), recent environmental, societal, economic and technological developments lead by I4.0 are changing manufacturing companies around the world and the market in which they do business. To cope with these challenges, companies need capabilities for managing their whole value-chain towards new BMs. Virtual and physical structures, allowing a close cooperation and rapid adaption along the whole product and system lifecycle, exploit digitalization and networking that enable the capability of transferring information in a very short time (Rajnai & Kocsis, 2018). This leads to globalizing markets, hence expanding businesses worldwide but also a hard competition to face. This introduce a main theme: the suitability of the company' system to enter the network broadening worldwide (Guenther Schuh, Potente, Varandani, & Schmitz, 2014), and the consequent need to have a clear view of their companies' readiness for the fourth industrial revolution for making the appropriate decisions to preserve or improve their competitiveness (Rajnai & Kocsis, 2018). This statement entails two main concepts: readiness and competitiveness.

Competitiveness of enterprises allows economies to be well positioned on the markets and to move forward new roles in value chains rapidly changing, for this reason (i) governments are assessing and driving the fitness of the local economy, and (ii) enterprises are interested to assess their readiness for I4.0 (Rajnai & Kocsis, 2018). In chapter two it has been provided a macro-understanding of I4.0 with a special focus on functions and technologies enabling a system 'I4.0-compliant', for the sake of identifying a 'scaly' technology stack suitable for I4.0 principles implementation. The suitability of these technologies, i.e. CPS, BD, IoT, for stating whether a system is 'I4.0-compliant' or not comes from relevant models for I4.0 implementation[66]. They allow (i) real-time availability of all relevant information, capacity to optimize processes at any time based on the information, integration of all participants of business to the value chain, i.e. both physical assets and processes, and business partners. From the point of view of business structure towards the I4.0 outcomes, several principles can be considered fundamentals to achieve the needed manufacturing flexibility and sustainability, and the value-creation network. Firstly, new level of organization and control of the entire cross-enterprise value-adding network throughout the product lifecycle, which includes (i) concept, (ii) development, (iii) production, (iv) order, (v) shipping, (vi) recycling, including associated services. This creates a real-time self-organizing system, optimized to various conditions like cost, resources usage and availability, and improved product quality towards satisfying customers' demand (Albers, Gladysz, Pinner, Butenko, & Stürmlinger, 2016; Rajnai & Kocsis, 2018). By decreasing the 'focal length' on technologies, and switching to the resources identified in chapter 2, hence broadening the angle of view, digitalization of physical assets and integration into digital ecosystems with value chain partners allows to realize I4.0 systems having the main impact of creating the desired value-network and characterizing new BMs based on new value-added services enabled by technology and function implementations[67] [68].

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[66] Source: Impuls: Industry 4.0 Readiness (Impuls-Stiftung. Aachen Cologne, 2015. Retrieved in Rajnai and Kocsis (2018).

[67] Geissbauer, R., Vedso, J., & Schrauf, S. (2016). Industry 4.0: Building the digital enterprise. Source: https://www.pwc.com/gx/en/industries/industries-4.0/landing-page/industry-4.0-building-your-digital-enterprise-april-2016.pdf. Last access: 2020.08.27

[68] Source: E.R. for C. in M. SCorPiuS, Validated sCorPiuS Vision, (2016) 1–17. Retrieved in (De Carolis, Macchi, Kulvatunyou, et al., 2017)

The digital transformation of interconnected companies is not technology investment only but entails an overall business strategy, internal and external the individual company, that lead to changing processes (Rüb & Bahemia, 2019). New business strategies are based on the commitment of the company management, and they require multiple steps involving technology and organizational changes. Moreover, the needs of skilled partners is stressed, for providing the technologies, services and knowledges required by the company (De Carolis, Macchi, Kulvatunyou, Brundage, & Terzi, 2017). Although they are more or less aware of the need to adopt changes to fit with the new industrial scenario (Rajnai & Kocsis, 2018), companies and especially SMEs are not able to understand the overall idea of I4.0 and to relate its principles to their business, failing to work out how to start with introducing industry 4.0, and further evolving towards systems eventually getting 'I4.0-compliant' for generating growth opportunities (Ganzarain & Errasti, 2016; Schumacher et al., 2016). Specifically, for the SMEs the problem of getting I4.0 compliant is more than implementing technologies for pushing processes and systems up traditionally streamline methods and techniques (especially in manufacturing), for instance, by increasing the productivity on the shop floor. But failing to understand the concept of interconnectivity of inside and outside systems through total integration practically thwart achieving production efficiency and effectiveness required by I4.0 (Ganzarain & Errasti, 2016), since only the collaborative implementation of all the concepts of I4.0 has to be followed to increase the productivity in production industries towards I4.0 (Günther Schuh et al., 2014).

The tardiness of SMEs lies in having limited financial resources that make difficult adopting new technologies and especially the digital transformation (Müller et al., 2018; Sommer, 2015). Additionally, SMEs have a deficit in networking opportunities since usually lack IT integration and adoption of software-based analytical tools; in addition, they lack the confidence to handle data management and security (Rafael, Jaione, Cristina, & Ibon, 2020). Beyond financial gap, SMEs face capacity and competence problems, and limited human resources (Müller et al., 2018; Sommer, 2015), less specialized in some areas of expertise than those in LEs, namely organizational culture and new technology implementation (Mittal, Khan, Romero, & Wuest, 2018). These aspects leads to not performing well in researching and developing new systems (Rafael et al., 2020). With respect to one of the main outcome of I4.0 r/evolution, SMEs fail to grasp potentiality of switching form product-orientation to service orientation, since they are not able to understand the meaning of diversification and to realize a holistic approach towards this opportunity: in fact, they lack awareness, knowledge, process, techniques and tools to envisage transforming (or simply, deepening) their business (Ganzarain & Errasti, 2016).

The lateness of SMEs is a matter of real concern in European scenario. An EU study[69] reports that about 77% of European SMEs are still unprepared to I4.0. In the 2021 EU program, three strategical axes have been identified to promote SMEs digitalization towards I4.0, namely (i) fostering knowledge and awareness of I4.0 paradigm, (ii) designing enabling platforms accelerating the transition, and (iii) promoting efficient methods and models for implementing development projects. Generally accepted and established methodologies for assessing Industry 4.0 readiness of enterprises are still dawning, since the phenomenon of the intelligent digital transformation of manufacturing still is in its emerging phase (Rajnai & Kocsis, 2018). This aspect leads to the concept of industry maturity level. Readiness encapsulates the concept of maturity, in the way that "the system must first be fully mature before it can be ready for use" (Tetlay & John, 2009). Maturity can be defined as *the state of being complete, perfect or ready*

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[69] Source: https://www.agendadigitale.eu/industry-4-0/industria-4-0-e-tempo-di-agire-il-piano-ue-a-sostegno-delle-pmi/. Last access: 2021.30.01.

(Kärkkäinen & Silventoinen, 2015; Mettler, 2009). It implies an evolutionary progress from an initial to a desired or normally occurring end stage (Mettler & Rohner, 2009).

A question arises: what does it mean to define a system mature for I4.0? As stated before, the vision of I4.0 in industrial systems is triggered by new forms of cooperative engineering and manufacturing aiming at: (i) improving SC resilience (Ivanov, Dolgui, & Sokolov, 2019; Schröder, Indorf, & Kersten, 2014), (ii) reinforcing the global competitiveness of companies (Porter & Heppelmann, 2014; Strange & Zucchella, 2017), (iii) enabling business model innovation (Frank, Mendes, Ayala, & Ghezzi, 2019; Müller et al., 2018; Reischauer, 2018), (iv) facilitating the development of a circular economy (Reischauer, 2018; M.-L. Tseng, Tan, Chiu, Chien, & Kuo, 2018) and sustainable business operations to society (de Sousa Jabbour, Jabbour, Foropon, & Godinho Filho, 2018; Stock, Obenaus, Kunz, & Kohl, 2018; Strandhagen et al., 2017). In order to realize such a system, the system exploits digitalization and communication network for capturing, processing and delivering data, making decentralized decisions and even acting as self-control systems (Brettel et al., 2014; Khaitan & McCalley, 2014). This means that technologies, i.e. SF, CPS, and IoT, realizes the I4.0, which means that the SMfg view triggers I4.0: SMfg can be interpreted as the software orchestrating sensors, actors, microchips, and autonomous systems for coordinating services and physical flows (Rafael et al., 2020).

The manufacturing system maturity relates to the introduction and adoption of applications, systems, and hardware (De Carolis, Macchi, Negri, & Terzi, 2017b) and generally concerns technology implementation, information connectivity, process tuning, organization setting, and personal capability development (Kulvatunyou, Ivezic, Morris, & Frechette, 2016). This is a process that involves development stages building one upon each other until maturity is reached (Kühnle & Bitsch, 2015; Lasrado, Vatrapu, & Andersen, 2015). An approach to map technology escalation and business conversion towards I4.0, are maturity models (Jæger & Halse, 2017). This approach cope with both the facts that companies (and especially SMEs) do not have suitable technologies (Moeuf et al., 2018), and they are afraid of the huge investments to be done (Theorin, Bengtsson, Provost, & Lieder, 2016), thus being capable of understanding their current level of maturity in their specific context (Becker, Knackstedt, & Pöppelbuß, 2009) for optimizing investments and resources consumption, and . Although there is a general consensus to use maturity models (MMs) to assess this maturity level (Schumacher et al., 2016), ofttimes industries cannot define what needs to be measured, because of largely discussed inability to grasp the I4.0 novelties and requirements (Schwab, 2017). Furthermore, a basic need for individualization of I4.0 for a specific system vision however not neglecting a collaborative vision between business partners has not to be taken for granted but seems still not really stressed in previous research (Ganzarain & Errasti, 2016). Consequently, the present chapter deals with the second and third research questions identified by this thesis, which is detailed by the needs for (i) identifying technologies and principles suitable to develop I4.0 systems within SMEs environments, and (ii) testing the actual effectiveness of the system consequent to implementing those technologies and principles. In fact, the genesis and the characteristics of I4.0 systems (i.e. Chapter 2), and the reference model RMI4.0 that implement a suitable I4.0 technology stack (i.e. Chapter 3) have been answered to the first research question, it is still pending how to realize such a system in SMEs environment. Most companies that are successfully implementing I4.0 are LEs, whereas there is still a long way to go for SMEs[70]. This drives to follow a customized approach to guide managers in the process, namely the MM should perfectly fit with the distinctive character of the sector (Piccarozzi, Aquilani, & Gatti, 2018) and contextual characteristics

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[70] Source: PWC, 2018. Europe Monitor - Innovation and Digital Transformation: How do European SMEs perform? Retrieved in: (Rafael et al., 2020)

of adopter firms (Mittal, Khan, et al., 2018; Tortorella & Fettermann, 2018). To answer to these questions a new maturity model is provided. Although generally applicable, the model is used to survey the state-of-the art of ER typical industries, especially those of the Parma area with which historical partnership with the University of Parma has been established. The maturity model has been designed under the research project "*Individuazione delle soluzioni tecnologiche abilitanti e modeling delle competenze richieste nella filiera alimentare della provincia di Parma*", funded by Fondirigenti[71], the Confindustria[72] and Federmanager[73] consortium' fund., project CIG 7817647E60[74]. The model has been designed with the collaboration of CISITA scarl[75] and SMILE DIH[76].

The reminder of the chapter is structured as follows. In section 4.1 an overview on MMs as research field is provided, introducing main rules to design a MM and research area of interest. Next in section 4.2, a comprehensive structured literature review of MM in I4.0 address the state-of-the-art of academic research from both quantitatively and qualitatively extents. This parts come from previous publication "*Maturity Models in I4.0: a Review*" by Bertolini et al. (2019), presented at the 25th ICPR Conference in Chicago and attached to this dissertation in Appendix 4-B. Next section 4.3 provides an overview of MM in practitioners' studies. The rest of the chapter is devoted to introducing the I4.0 MM proposed by this work, i.e. the Digital Maturity Index for I4.0 (DMI4.0): its design, the environment to which has been validated, the results achieved by the survey. Last section addresses conclusions: beyond discussing insights and results, it is discussed how the DMI4.0 could support new BM design. Although BMs are not the core topic of this thesis, a quick mention to possible directions to follow have been judged useful. For better understanding these, a brief overview of BM theory is also provided.

4.1 Description of MM research area

MMs are models of objective assessment of status quo for object improvement in a step-by-step pattern (Gausemeier, 2009). They are structured in levels for mirroring stages of growth that an organization passes through, which have three main distinctive elements (Gottschalk, 2009): (i) they follow a particular order, (2) they have a hierarchical progression not easily reversible, (3) they involve lots of organizational activities and structures. Hence they provide a basis for 'strategic planning' of investments, so as to ensure continuous improvement and to move towards corporate objectives (Hackos, 1997). Fraser et al. (2002) have provided a clear classification of maturity models according to three typologies identified. Next characterization descends form that work. First typology is the maturity grid, which typically illustrates maturity levels in a simple and textual manner, structured in a matrix or a grid. They are of somehow simple and they do not specify direction towards which to aim. They only identify some characteristics that processes, and enterprises should have in order to reach high performance (Maier, Moultrie, & Clarkson, 2011). Second typology is the Likert-like, that are constructed by "questions" as statements of good practices. Responders to the questionnaire must score the related performance on a scale of N values. Hybrid models as a combination of the questionnaire approach with the maturity grid do exist. Finally, the CMM-like models (CMM stands for Capability Maturity Model) identify the best practices for specific processes and measures the maturity of organizations in terms of how many practices are implemented (Maier et al., 2011). Their architecture is more structured and complex, compared to the

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[71] https://www.fondirigenti.it/
[72] https://www.confindustria.it/en
[73] https://www.federmanager.it/
[74] https://www.smile-dih.eu/fondirigenti-digital-skills-for-the-food-industry/?lang=en
[75] https://www.cisita.parma.it/
[76] https://www.smile-dih.eu/?lang=en

other. Structure is divided into process areas sharing some common features, which specify several key practices to address a series of goals. Typically, also the CMM-like models exploit Likert questionnaires to assess the maturity.

A further development of CMM-like model is the Capability Maturity Model Integration that provides guidance to perform processes of different nature[77].

Generally, MMs share some common proprieties (De Carolis, Macchi, Negri, et al., 2017b; Fraser et al., 2002):

- Maturity stages: it is generally adopted a scale of levels from three to six, but this is not mandatory. For instance, the MM for IoT of Jæger and Halse (2017) has eight levels. Levels cope with the step-by-step stage of growth of the system towards the maturity, i.e. the highest level in the scale.
- Descriptors for each level: these provide a suitable name for each level.
- Description of the characteristics of each level.
- Dimensions: they are the clusters for mapping the maturity into different areas, providing a detailed representation of the current and future state.
- Items: are elements or activities grouped into dimension, for surveying the system.
- Descriptions of activities that must be performed at each maturity level.

Another key characteristic for distinguishing the design of MMs is represented by the assessment and the measurement typology (Schumacher et al., 2016). The measurement typology and tools to visualize measures depend on the purpose to achieve, and the main purposes of assessment instruments are: (i) descriptive, i.e. providing a picture of the AS-IS situation of the organization; (ii) prescriptive, i.e. indicating how to approach maturity improvement; (iii) comparative, i.e. enabling benchmarking across companies (De Carolis, Macchi, Negri, & Terzi, 2017a).

4.1.1 The MM research area in industrial context

Useful attempts to organize the MM design have been made in last twenty years, aiming at (i) providing the main phases of generic model development (De Bruin, Freeze, Kaulkarni, & Rosemann, 2005), and (ii) defining a structured method to develop a specific MM (Becker et al., 2009). The design method proposed by Becker et al. (2009) is well-accepted by academia and practitioners: it has been cited 846 times in Google Scholar, until 27th March 2020. Authors define a general procedure model in eight phases and seven requirements. Phases are: (P1) problem definition, (P2) comparison of existing models, (P3) determination of the design strategy, (P4) iterative maturity model development (broke up into selecting the design level, selecting the approach, designing the model section, and testing the results), (P5) conception of transfer and evaluation, (P6) implementation of the transfer media, (P7) evaluation, and finally (P8) rejection of the model. Requirements are: (R1) Comparison with existing maturity models, (R2) Iterative Procedure, (R3) Evaluation, (R4) Multi-methodological Procedure, (R5) Identification of Problem Relevance, (R6) Problem Definition, (R7) Targeted Presentation of Results, (R8) Scientific Documentation. Each phase meets one or more requirement as its developing procedure, hence a matrix to indicate the relation between phases and stages is proposed in Table 4.1.

On the other hand, De Bruin et al. (2005) are pioneers of the definition of MM design. Their six-step framework entails defining the (i) 'scope' of the model and its (ii) 'design' as the architecture of the model. Next steps deal with (iii) 'populating' the model, i.e. where to search subjects to be surveyed and how to

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[77] Source: CMMI Project Team (2002). Capability maturity model® integration (CMMI SM), version 1.1. Retrieved from ftp://ftp.sei.cmu.edu/public/documents/02.reports/pdf/02tr028.pdf. Last access: 2020.08.27

gather the content. Finally, follows the (iv) ‘test’, (v) the ‘deployment’, and the (vi) ‘maintenance’ phase, which asks to continuously update the model. First two steps are relevant since are preparatory to others. The former step allows to set the outlying boundaries for model application and use: it requires to define the focus of the model and the development stakeholders. The latter forms the basis for further development and application. It requires to define five criteria: (i) the audience, (ii) the method and the (iii) the driver of application, (iv) the respondents and finally (v) the end application.

Table 4.1 - requirements to develop each phase of the procedure model in Becker et al. (2009)

	R1	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**
P1					X	X		X
P2	X							X
P3								X
P4		X						X
P5				X				X
P6							X	X
P7			X					X
P8								X

Figure 4.1 simply depict the framework for designing maturity models according to De Bruin et al. (2005). The cycling graphics wants to highlight that the maintenance phase allows to update and improve the model redefining what was set in the previous design.

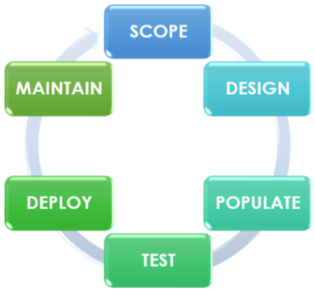

Figure 4.1. Six-step framework for designing a MM rearranging De Bruin et al. (2005)

The follow analysis of research on MM comes from the quantitative study of Bertolini et al. (2019) pertaining the studies carried out for this thesis, in which authors have analyzed 65 relevant papers on maturity in business management towards both business intelligence and operations management.

Firstly, they have grouped the papers over years of publication, determining the frequency of publications per year for providing the trend of the general literature (Figure 4.2).

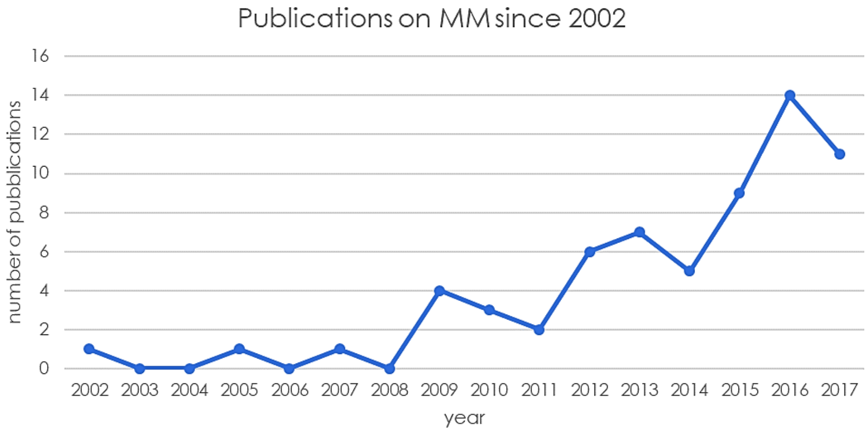

Figure 4.2. Publications over years on MM in the timespan 2002-2017 (Bertolini et al., 2019)

The number of publications is basically increasing since 2002, i.e. the year of the first publication of list of 65 papers, and form 2015 onwards a considerable interest in it has been arising. The analysis stops in 2017 because of its set-up in retrieving the papers.

Next, authors have identified 19 research areas and 8 subject categories clustering the areas, by the content of titles and abstracts, and keywords. Then, the documents have been grouped with regards to the subject categories and the research areas by reading the full paper. Finally, the frequencies of each research area and subject category are determined. Figure 4.3 and Figure 4.4 provide the full lists of research areas and subject categories, respectively, and their occurrences.

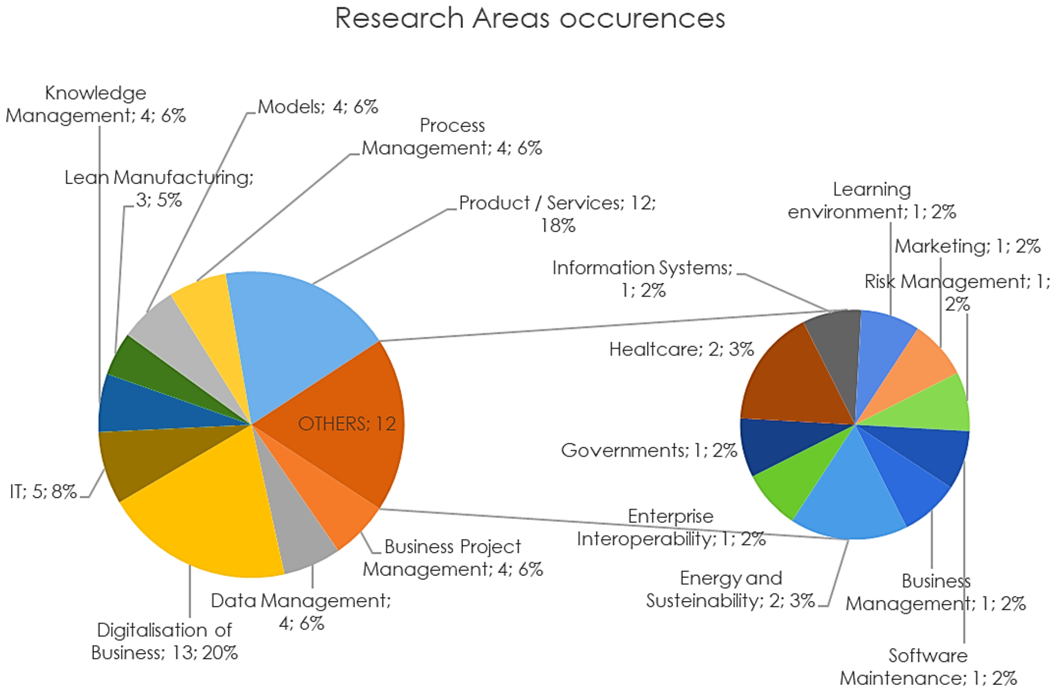

Figure 4.3. Research Areas of studies on MM (Bertolini et al., 2019)

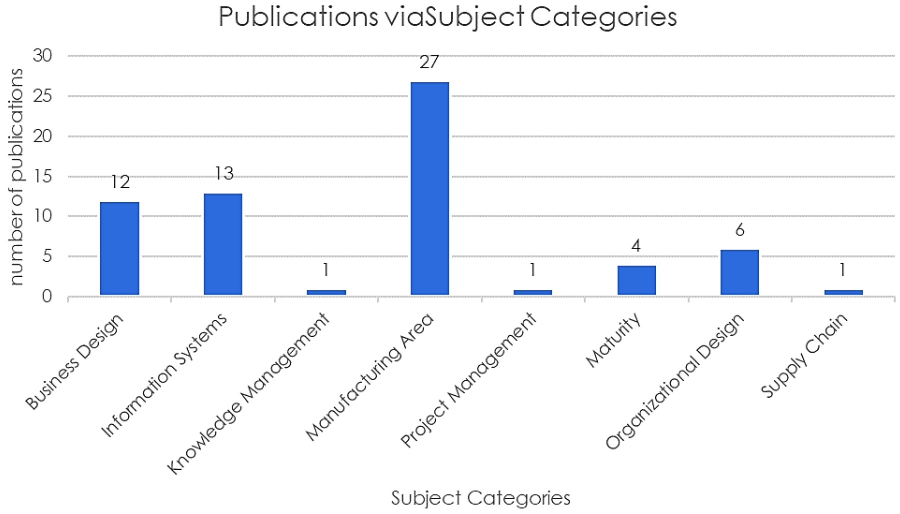

Figure 4.4. Subject Categories of research on MM (Bertolini et al., 2019)

Follow considerations stick to the authors' considerations (Bertolini et al., 2019):

> *The most of publications belongs to the manufacturing area, and they aim at defining a MM for the digitalization of business and the development of products and services. Other research area interested in MM belongs to the business design, and the information systems: a possible cause of this result is the relation between these research areas, which are concurrent because of their multi-disciplinary. It is important to note that 20 of 65 documents are Literature Reviews and just provide insights on the maturity model for specific research area.*

The analysis shows that the concept of maturity and MMs have attracted in recent years lots of research communities as about the 70% of the literature on this topic in the timespan surveyed (i.e. 2002-2017) has been published in its last five-year period (2013-2017). Research cores relate to digitalization of business, product and service provisioning, and IT infrastructure deployment. This sounds as I4.0 is somehow affecting MM research, and the result is not fuzzy. In fact, since the structured idea of I4.0 has appeared as a complex system of technologies and their paradigms for achieving a higher level of operational efficiency and productivity, manufacturing operations, and business strategies (Hermann et al., 2016; Kagermann et al., 2013), it attracted more and more attention in several research field, hence also the MM.

4.2 A review on MMs in I4.0 of academic literature

The same work of Bertolini et al. (2019) has reviewed in quantitative and qualitative way the literature on MM in I4.0.

> *As expected, a field in which the application of MM has raised a great deal of attention is I4.0. Since the concept of I4.0 has become of public interest, organizations and companies of any dimension and sector have started asking themselves 'how far have I evolved in the I4.0 scale?'*

The authors started from a database of 108 documents gathered from Scopus, then they first neglected 42 papers (not suitable because of they were not available on the web, or they lacked information for the analysis). The remaining 66 papers have been analyzed quantitatively for achieving knowledge on the MM in I4.0. Then, by reading the titles and the abstracts, authors have identified 9 main documents for depicting general rules adopted by researcher in dealing with MM design for I4.0 towards manufacturing operations optimization and business intelligence innovation.

The quantitative analysis of the documents from the TARGET list relates to clustering the authors' keywords. Total amount of 210 keywords have been normalized merging different keywords used for a same topic, e.g. CPS and Cyber-Physical Systems, and neglecting singular and plural declinations. Then have been identified 27 main headings (i.e. headers) to label the normalized keywords. Next, keywords have been grouped into 6 different clusters relating to I4.0 (i.e. three clusters), MM (i.e. two clusters), and applications (a single cluster). Clusters adopted are: (i) 'Business Innovation', which refers to innovation in knowledge management and business intelligence towards I4.0; (ii) 'ICT' which refers to information technologies required for I4.0 implementation; and (iii) 'IIoT', preferred to the label IoT since it allows also to also take into account keyword relating to manufacturing processes; (iv) 'Maturity', which relates to terms addressing the concept and implementation of maturity, e.g. also 'reference architecture'; (v) 'Method', which relates to methods and techniques adopted to assess the maturity level (e.g. assessment and KPI); and finally (vi) 'Users', identifying the environment in which apply the MM or the funding institutions and their perspective. Table 4.2 provides the cluster list and the relative headers, and the number of occurrences for each of them.

Authors (Bertolini et al., 2019) provides the following insights to the quantitative analysis.

> *The frequency of the headers, within a same cluster, is almost comparable except for some singularity. On the contrary, it is interesting that in this literature as few as 25% of keywords are related to the themes of maturity.*

Another issue concerns the fact that lots of literature (about the 50%) is dedicated to reviewing existing literature, that suggest that studies on MM in I4.0 have been significantly aimed at categorizing and comprehending existing knowledge, thus subtracting time and effort to the development of new models (Bertolini et al., 2019).

> *This seems to suggest that the I4.0 literature approach concerns more the discussion on maturity rather than the design of MMs. It looks like if an innovative approach is still missing from MM literature, which is quite surprising because literature on maturity is far from well-established.*

As a result next insight flows (Bertolini et al., 2019).

> *The literature on maturity in I4.0 tries to understand how to measure maturity and what to measure. However, it generally misses to address how to define the suitable maturity benchmark, and what are the eventual effects of the industrial revolution on individual practices towards servitization, business intelligence and interoperability.*

Table 4.2 - Headers and cluster of the authors' keywords used in literature on MM in I4.0

Clusters	**CLUSTER occurrences**	**Headers**	**HEADERS occurrences**
IIoT	(78)	CPS; Digital Twin; Industry 4.0; IoT; Revolution 4.0; Servitization; Smart Factory (Mfg)	(11); (12); (14); (18); (7); (6); (10)
ICT	(27)	Agility; Algorithms; IC; Interoperability	(11); (4); (8); (8)
Business Innovation	(12)	Business Intelligence; Knowledge Management	(8); (4)
Maturity	(20)	Architecture Framework; Maturity Model	(7); (13)
Methods	(32)	Assessment Method; Gap Analysis Method; Holistic Approach Method; Key Performance Indicators (KPI) Method; Literature Review; MCDM Method	(7); (1); (1); (12) (4); (7)
Users	(41)	Energy&Environment; Engineering; Industry (Geo/Sector); Projects; SMEs; Use Case	(6); (16); (8); (1); (5); (5)

The second part of the review is devoted to the qualitative analysis of the 9 main documents on MM in I4.0 (especially towards SMEs), in the form of a document review focused on core characteristics of the model, named by the authors 'document outline'. Two main steps to design a MM as defined by De Bruin et al. (2005), i.e. 'design' and 'populate' have been used to identify the core characteristics of the models. Core features to describe the models are mapped onto criteria of two steps. In particular authors (Bertolini et al., 2019) have used the number of stages, the number and typology of dimensions, and the framework for measuring the level of maturity, for distinguishing among model designs. The 'design' of the model identifies: (i) the 'dimensions' to measure, relates to the application components; (ii) the 'measurement of the maturity', relates to the audience, the respondents, and the method application; the last one addresses also (iii) the 'calculation tool', and (iv) the way to express the 'results'; finally, (v) the 'maturity stages', relates to the audience. The 'populate' step relates to the 'control' stage. The map of the relation between core steps in De Bruin et al. (2005) and the identified core features to outline the MM is provided in Figure 4.5. The outline of analyzed studies is provided in Table 4.3. Dimensions are selected according to the relevance of I4.0 to strategic goals to achieve and to structure of the organization to which the model is aimed. Items are the measurement point to grasp the state-of-the-art of the organization with respect to the goal pursued. The maturity survey generally lies in a static linear combination (weighted average on KPI) between element of dimensions and items measured through assessment. For instance, the MM provided by Schumacher et al., (2016), a real literature classic (cited 538 times in Google Scholar[78]), is a perfect sample reflecting this general rules. Dimensions map the company surveyed onto a universal description of enterprises structure. Items, in the form of questions, ask people to self-assess their company maturity with respect to specific I4.0 elements, i.e. manufacturing technology and practices, and business arrangement. Calculating rules combine the answers of company' staff and importance of dimensions towards I4.0 view of business. Graphic provides a simple and appealing results at-a-glance, for both individual dimensions and combining them for a whole picture.

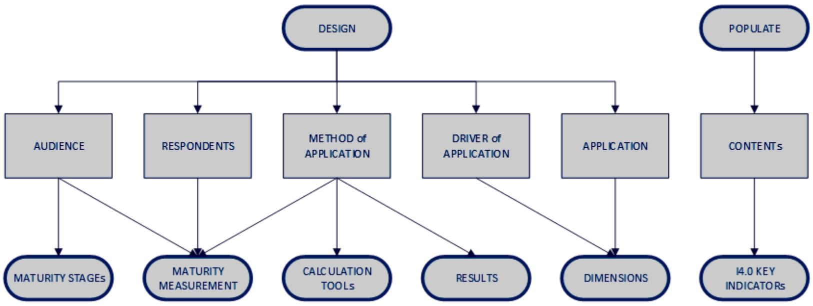

Figure 4.5. Relations between core steps in De Bruin et al., 2005 and core features to outline MM in I4.0 (Bertolini et al., 2019)

In the following a brief description of the other models is provided.

Modrak et al. (2019) have provided a maturity self-assessment method (even if authors talk about readiness, the model is a MM) for a (subjective) roadmap model. Authors have identified the three areas of intervention, i.e. (i) smart logistics, (ii) smart production, and (iii) organizational and managerial models. Each area is divided into five categories and the maturity of each category must be assessed through five levels of maturity. People must evaluate the maturity of the current state, and the expected level of maturity possible to achieve, which is the target of the future state. Calculation tools is obtained by means of linear combination of importance of the requirement for the future state, valuation of its current level and of its required future level. Results are provided by means of a spider graph. The validity of the results is proven by the correlation of answer provided by means of calculation of Cronbach α.

Ganzarain and Errasti (2016) have designed and approach to assess maturity as a framework for enabling a project for development of a I4.0 system. Assessment consists in 5 levels of maturity with respect to specific requirements and possibilities offered by I4.0 to company evaluating its maturity.

Bibby and Dehe (2018) have developed an assessment model to measure the level of implementation of I4.0 technologies in industrial SC, testing the model in the defense sector. Authors have defined three dimensions, i.e. 'Factory of the Future', 'People and Culture', 'Strategy'. Dimensions consist in total thirteen attributes, which are clustered coherently with the meaning of each dimension: for instance, attributes of the dimension 'Factory of the Future' relates to the enabling technologies of I4.0 as identified by the authors. The assessment has involved fourteen experts of the SC, answering questions (i.e. the items of each attribute) by means of a Likert rating scale scoring from 1 to 5. The result is provided in a maturity-grid manner, namely by a ranking.

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[78] Last access: 2020.08.29

Table 4.3 - Outline of main MMs in I4.0 as in (Bertolini et al., 2019)

Title of publications (Authors, Year of Publication)	**Dimensions**	**I4.0 Key Indicators**	**Maturity Measurement**	**Calculation Tool**	**Presentation of Results**	**Maturity Stages**
"A maturity model for assessing industry 4.0 readiness and maturity of manufacturing enterprises" (Schumacher et al., 2016)	9 dimensions related to the company organizational units, 62 items	practitioners' assessment on I4.0 topic	assessment by questionnaire to be answered by users	weighted average on KPI	radar-chart graphics	5 stages
"Mapping requirements and roadmap definition for introducing i 4.0 in sme environment" (Modrak et al., 2019)	3 areas related to smartification and business development	literature review + multi-case study on SMEs	assessment by questionnaire to be answered by users	weighted average on KPI (dimension and measured item)	spider-graph graphics	5 stages
"Three stage maturity model in sme's towards industry 4.0" (Ganzarain & Errasti, 2016)	4 focuses, i.e. Energy, Electronic, Digital Business, Advanced Metal Mechanics	experts' interviews and technological partners' opinion	Interviews	-	-	5 stages
"Defining and assessing industry 4.0 maturity levels–case of the defense sector" (Bibby & Dehe, 2018)	13 key attributes related to technologies and business and knowledge management	literature review	assessment by questionnaire on focal firm and VN	weighted average on KPI (dimension and measured item)	Ranking	4 stages
"Development of a digitalization maturity model for the manufacturing sector" (Canetta, Barni, & Montini, 2018)	5 sections related to company departments	literature review	assessment by dynamic questionnaire	weighted average on KPI (dimension and measured item)	radar-chart	3 stages + overall level
"Towards a smart manufacturing maturity model for smes (sm3e)" (Mittal, Romero, & Wuest, 2018)	5 organizational dimensions	literature review and interviews to SMEs' expert	domain-mapping matrix relying on toolboxes	Toolboxes (combination rules not provided)	3D-chart graphic	5 stages
"A maturity model for assessing the digital readiness of manufacturing companies" (De Carolis, Macchi, Negri, et al., 2017a)	4 dimensions to be met by the manufacturing backbone, i,e, 5 process areas	literature review and experts' interview (both academia and practitioners)	assessment by questionnaire	linear combination of dynamic weights and indexes	-	5 stages
"Development of an assessment model for industry 4.0: Industry 4.0-MM" (Gökalp, Şener, & Eren, 2017)	5 aspects dimensions related to assets, data, process and organizational management	literature review	as in ISO/IEC 15504 (former spice)	as in ISO/IEC 15504 (former spice)	as in ISO/IEC 15504 (former spice)	5 stages
"Concept for an evolutionary maturity based Industrie 4.0 migration model" (Leineweber, Wienbruch, Lins, Kreimeier, & Kuhlenkötter, 2018)	3 dimensions, i.e. technology, organizational and personnel, and 44 criteria to meet	analyzed by the chair of production systems at the Ruhr-University of Bochum	-	weighted average on KPI (dimension and measured item)	stage representation	4/7-stages depending on the meeting criteria

Canetta et al. (2018) have developed their 'Digitalization Maturity Model' to assess the current state of companies towards the I4.0 future state, manly lying in digitalization, as the name of the model reveals. The MM is the first step of a three-step framework for reaching the desired future state. A questionnaire whose thirty-six questions are grouped into five dimensions 'Strategy', 'Processes', 'Technologies', 'Products & Services' and 'People' is submitted to the company. Second step involves corporate reference personnel involved in structured interviews for tracking (i) technological infrastructure used, and (ii) process needs (computerization level, connectivity, visibility, predictive ability, and adaptability), for main processes of the company. The third step provides an in-depth analysis of the activities carried out within each process in order to define how the integration of I4.0 technologies and methods, and the related modification of the activities, brings to a change in the working conditions and related skills towards digitalization and I4.0 practices. The maturity level preparatory to the other steps is computed by linear combination of a weighting factor depending on expected results, and the importance of questions according with the characteristics of the company, which is obtained by the answers of company personnel to the first dimension. With this regards it is important to note that authors state that aspects as production strategy (e.g. MTS vs ETO), as well as production method (e.g. batch vs flow), and the independency degree of the company (e.g. single company vs part of a group) are fundamental for understanding which type of processes the company is interested to digitalize, and the priority list for intervention. Results are visualized by radar-chart graphic.

Also Mittal, Romero, et al. (2018) have proposed a MM focused on digitalization. Their target is the SMfg implementation within small and medium-sized Enterprises. The SM^{3}E MM is structured as a three-axis model consisting of: (i) organizational dimensions, (ii) toolboxes, and (iii) maturity levels. 'Dimensions' are the five area to map towards I4.0 maturity and mimic the usual SMEs' organization. They are: (i) Finance, (ii) People, (iii) Strategy, (iv) Process, and (v) Product. Each dimension has a different number of sub-dimensions somehow representing intervention areas. 'Toolboxes' are methods, tools, and practices that include operational and information technologies, personnel' skills and business practices leading to technical and managerial implementation of SMfgs. The whole SM^{3}E toolkit is composed of seven toolboxes to judge the current state implementation: (i) manufacturing/fabrication toolbox, (ii) design and simulation toolbox, (iii) robotics and automation toolbox, (iv) sensors and connectivity toolbox, (v) cloud/storage toolbox, (vi) data analytics toolbox, and (vii) business management toolbox. The 'Maturity levels', expressed in a CMMI-like scale (i.e. 5 stages). The final representation could be viewed on the three-axis model connecting the coordinates.

Digital readiness of manufacturing is central also to De Carolis, Macchi, Negri, et al. (2017a). Authors have designed DREAMY - Digital REadiness Assessment MaturitY model - to measure whether "*manufacturing companies are ready to go digital*". The MM is based on the inspiring principles of the CMMI (Capability Maturity Model Integration) framework, and from this architecture copy the five-level scale of measurement. Four dimensions, i.e. (i) Process, (i) Monitoring and Control, (iii) Technology, and (iv) Organization are used to assess maturity through five areas in which are grouped manufacturing key processes: (i) design and engineering, (ii) production management, (iii) quality management, (iv) maintenance management, (v) logistics management. 'Digital Backbone' is the thread connecting areas and dimensions. Maturity is ranked from low to high level of maturity according to desired set-up of practices. According to the score achieved, criticalities in implementing the digital transformation and to subsequently drive the improvement of the whole system are addressed as suggesting the suitable implementation framework. The maturity assessment is carried-out by means of the 'Digital Readiness Questionnaire', whose answers are structured according to an increasing level of maturity. Questionnaire and calculations are dynamic, meaning that the dimensions enabled replying the questions depend on previous answers[79].

The 'SPICE-based Industry 4.0-MM' by Gökalp et al. (2017) is an assessment of process transformation, application management, data governance, asset management, and organizational alignment areas. It has the dual aim of (i) surveying the I4.0 maturity of companies, and (ii) defining their evolution towards new maturity stages. Authors have used the SPICE - Software Process Improvement and Capability dEtermination – maturity architecture (then replaced with ISO 33000 series[80]) because of "*its well defined and commonly accepted structure for the assessment and improvements and its suitability for the development of maturity level assessment of organizations in the context of Industry 4.0*". The MM is a two-axis model consisting of (i) 'Aspect dimension', and 'Capability dimension'. Former dimension has a holistic view of companies, and it consists of 'Asset Management', 'Data Governance', 'Application Management', 'Process Transformation', and 'Organizational Alignment areas'. Latter dimension allows the formulation of a roadmap in all relevant areas with a step-by-step approach, in the form of a succession of capability stages, from the basic requirements for Industry 4.0 to the full implementation. Maturity level and next step for implementing next I4.0 features are patterned on the two-axis coordinating system.

Bertolini et al. (2019) have also considered the literature review of Leyh et al. (2017) focused on digitalization, especially of Lean Production systems towards their I4.0 upgrade. However, this work is a review of I4.0 and Lean Production for defining dimensions suitable to the desired assignments. Thus, in the literature review of this dissertation is neglected.

4.2.1 Outlooks for the MM in I4.0

Some considerations to the literature review, directly come from Bertolini et al. (2019).

From the quantitative analysis it could be somehow asserted that literature on *maturity* and MMs seems somehow late in keeping the pace of innovation of I4.0 (Bertolini et al., 2019).

From the qualitative analysis, the authors (Bertolini et al., 2019) state that:

> *All models reviewed rely on surveys of users' opinion through assessment and questionnaires, hence the current maturity levels depend more on socio-cognitive basis (e.g. perception and acceptance to use), rather than on the objectively measurement of technology and knowledge stack*

Some other considerations can be made, which are relevant to identifying the outlooks for future works.

Firstly, the majority of MM are focusing on SMEs. This statement somehow replies to the research question (RQ2) of this thesis, assessing that SMEs deserve particular attention. Furthermore, the literature review highlights that it seems to lack an approach that deals with the specificity of each reality, namely each company needs to be mapped as stand-alone reality because of its characteristics and the particularity of the industry in which it makes business. For instance, a generally approach misses the specificity of processing industry, which rules are pretty different form traditional manufacturing ones, as well as difficulty it is not demonstrated how such a characterization meets hybrid XTO strategies (namely differing from Make-to-Stock) in which indicators for judging efficiency, flexibility, and sustainability are different since are different the results possible to achieve. Although this is generally recognized, models that manages this characterization are still not designed.

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[79] Self-assessment is available from http://preparatialfuturo.confindustria.it/. Last access: 2020.08.30

[80] Source: ISO, I. (2015). IEC 33020: Information technology: Process assessment: Process measurement framework for assessment of process capability. Retrieved in Gökalp et al. (2017)

Secondly, all models are mainly triggered by the rising adoption in industrial context of IoT and are driven by the even increasing need to digitalize assets, processes, and knowledge. This aspect somehow replies to the need for identifying basics of I4.0: digitalization and networking are suitable to describe the big picture of I4.0, moreover they are technology components to consider when surveying the I4.0 capability of companies, since they are enough to understand if companies are moving forward to the I4.0.

Thirdly, literature on MM in I4.0 seems to generally prefer a pilot-scale up approach. It is opinion of who write this dissertation, from the experience gained in these years of research, that is more suitable considering the journey towards the I4.0 as an iterative approach towards optimization of technical infrastructures, operations processes, and business practices. This pattern let companies mature into I4.0 blue-chip companies, as just iterative approaches allow. In fact, it is well-proven that just continuous reconfiguration and re-invention of organizations' structures and processes allow to respond to challenges and turbulence coming from systems' evolutions (Bessant & Caffyn, 1997), and repeated circular interaction among sub-structures and sub-processes let hit the target (Moen & Norman, 2006).

Finally, although all studies cite the term 'Business Models' and discuss the need for a roadmap implementing I4.0 more than just an assessment of maturity/readiness, real insights into BM innovation still lack. It seems that research on MMs puts its effort into suggesting 'how' to react to environmental r/evolution, whereas they miss to suggest the eventual outcomes of the suggested interventions for each specific reality, namely they miss to specify 'where' is suitable to intervene.

4.3 Practitioners' MMs: an overview

Tools for assessing maturity have been developed both by academia and organizations externally involved in industrial practices, with the twofold aim of (i) providing analytical frameworks that companies could adopt to self-assess their level of maturity with respect to specific interests, as well as (ii) cooperating with same companies in defining a framework for growing a next level of maturity (Chanias & Hess, 2016). Canetta et al, (2018)In have started from the review carried out by Chanias and Hess (2016), extending it with a classification of the analyzed maturity models with a focus on readiness, maturity, and industry 4.0 and digitalization of course. This section starts from this review and integrates it with other relevant contributions discovered in the research activities performed towards this dissertation. Full list of relevant practitioners' model is provided in Table 4.4. Rearranging Canetta et al. (2018), models are clustered with respect to their application purpose as identified by De Carolis, Macchi, Negri, et al. (2017a), and it is possible to note that the majority of models aims at just providing company with insights about their level of adoption of I4.0 technologies. Motivation is supposed to be the fact that practitioners' organization are more interested in (i) "*providing companies with tools used to highlight their maturity gaps and offer, on the base of the results, consultancy services*", and (ii) "*to obtain sectorial data, relevant for their market analysis/strategies*" (Canetta et al., 2018). Each model is then characterized by means of: (i) the application typology, i.e. 'Domain', which can be general purpose vs specific; (ii) the 'Assessment' method, i.e. if the maturity level is surveyed by self-assessment rather than by a third part; finally (iii) the measurement typology, i.e. whether (i.e. 'linear') or not (i.e. 'non-linear) the model computes values by means of linear combination of judgement values and weights. Although some models are of scientific nature, they are designed in partnership with organizations and companies, e.g. the model by Rong (2014) which has been developed in collaboration with Rockwell automation. Then, they are considered practitioners' MMs.

Among models listed, according to Schumacher et al. (2016) one of the most scientifically reliable and structured in a transparent manner is the model provided by Lichtblau et al. (2015): 'IMPULS – Industrie 4.0 Readiness' consists in a comprehensive dataset well-detailed about dimensions, items and measurement rules. The self-assessment pattern is structured in 6 dimensions including 18 items, and 5 maturity levels. Next stage of maturity possible to achieve are enabled by defined barriers to overcome by following specific advices.

Table 4.4 - Some of the most important MMs provided by practitioners' organization as retrieved in Canetta et al. (2018) *and other works. Dash '-' stands for 'information not available'*

Application purpose	**Study[81]**	**Domain**	**Assessment**	**Measure**
Descriptive	Friedrich et al. (2011)	general	self-assessment	linear
	Westerman et al. (2011)	general	self-assessment	non-linear
	Berghaus et al. (2015)	general	third-party assisted	linear
	Catlin et al. (2015)	general	-	linear
	Digital Excellence in Pharamceutical Industry (2015)[ii]	specific – digitalization of Pharma industry	self-assessment	linear
	Digital Maturity Assessment (2015)[iii]	general	self-assessment	non-linear
	Digitale Trasformation in die smart Fabrike (2015)[iv]	general	-	non-linear
	The Digital Trasformation of Industry (2015)[v]	general	self-assessment	linear
	Accenture (2016)[vi]	specific – focused on knowledge management	-	linear
	Ein Benchmark für die digitale Agenda (2016)[vii]	general	self-assessment	linear
	Opitz et al. (2016)	general	third-party assisted	non-linear
	Digitalisierungsindex Mittelstand (2018)[viii]	general	self-assessment	linear
Comparative	dStrategy Digital Maturity Model (2012)[ix]	general	self-assessment	linear
	Gill et al. (2016)	general	self-assessment	linear
Prescriptive	Rong (2014)	specific – connection of OT/IT	third-party assisted	-
	Lanza et al. (2016)	general	self-assessment	-
	Digital Maturity Assessment (DMA) (2017)[x]	general	third-party assisted	-
Comparative & Prescriptive	Lichtblau et al. (2015)	general	self-assessment	-
	Industry 4.0 - Enabling Digital Operations (2016)[xi]	specific – digitalization of aeronautic industry	self-assessment	linear
	Günther Schuh et al. (2017)	general	third-party assisted	-

As observed by Canetta et al. (2018), also for these models a general approach in which MM are designed more for providing consultancy services rather than for fostering I4.0 dissemination and implementation of use cases. However, to the knowledge of who write this dissertation, the Acatech' study 'Industrie 4.0 Maturity Index – Managing the individual digital transformation of companies' (Günther Schuh et al.,

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[81] Where link or document lack, reference is provided as a closing note to the bibliography. Information is provided as in Canetta et al. (2018)

2017) is one interesting application of the MM concepts to the I4.0. In the next subsection a full description of the model is provided, also as a sample for letting the reading better understand the structure of a MM before to describe the MM designed in this thesis.

4.3.1 The Acatech' Industrie 4.0 Maturity Index

The national academy of science and engineering 'Acatech' promotes sustainable growth through innovation, providing policymakers and society with evidence-based advices of public interest.

The MM provided wants the companies to be aware of how leveraging potentiality of data according to the characteristics of the industry sector and their individual organizational structure and culture.

A first stage of the process to assess the maturity consists in defining the current state of the company (i.e. strategies, objectives, technologies, and systems, as well as desired benefits and intervention priorities) by means of a structured multiple-choice questionnaire. The maturity is assessed in 6 development stages as a pattern towards the expected digitalization level of the company. Each stage describes the capabilities, required in order to attain this level, of 4 structural areas involving each one 5 functional areas representing the corporate (i) structures, (ii) processes, and (iii) strategies. Maturity is represented on a radar graph whose two axes for each structural area represent two principles that depend on the same structural area. It is possible to state that the structural area defines the questionnaire section, the functional area tunes the item typology to specific target, principles address the eventual item of the questionnaire.

Then, a roadmap for developing a digital strategy for the whole company' business is defined by means of a step-by-step approach. The roadmap comprises two other stages beyond the first. The second stage askes the company identify the target level of maturity that it wishes to reach at the end of the transformation processes, according to the own corporate strategy. A gap analysis is used to identify the missing required capabilities that company still needs to develop towards the desired maturity level. Finally, the third stage involves practically plan actions and strategies for achieving the desired maturity level previously defined.

Table 4.5 recaps the general structure of the Acatech' MM as described by Günther Schuh et al. (2017). The structure provides (i) the baseline for setting the questionnaire and (ii) a reference for addressing the maturity roadmap.

Table 4.5 - An overview on the Acatech' maturity model structure (Günther Schuh et al., 2017)

5 functional areas involved	**4 structural areas**	**principles (horizontal axis, vertical axis)**
development ***production*** ***logistics*** ***services*** ***marketing & sales***	*Resources*	*Digital capability, Structured communication*
	Information systems	*Integration, Information processing*
	Culture	*Internal organization, Collaboration in VNs*
	Organization' structure	*Willingness to change, Social collaboration*

4.4 <u>The Digital Maturity Index for I4.0 DMI4.0</u>

In this section the description of the DMI4.0 is provided. The MM answers to (RQ2) and (RQ3) of this thesis, namely:

(RQ2) Does a maturity model exist that simply shine a light on principles and technologies to develop I4.0 systems within SMEs environment?
(RQ3) Is the maturity model introduced effective and viable?

In doing it, the MM is practically designed developing a case study of the agro-food industry of the food valley, and then is tested in this environment. However, it has been designed for being a general-purpose MM.

The reminder of the section is described in the next subsection that provides the research methodology adopted.

4.4.1 Research methodology

Firstly, an analysis of studies relevant to identifying general requirements of industrial business is developed, then a survey involving the manufacturer of industrial machineries and plants in the form of unstructured interviews (Burgess, 2002) is conducted. Unstructured interviews have been preferred to structured questionnaire since they allow to conduct the interview without biasing the interviewees or influencing their responses (Y. Zhang & Wildemuth, 2009). SC of interest is the agro-food one, among the most important of national[82] and local[83] economy. The survey is carried out with the twofold aim of (i) achieving a whole description of the industrial sector, and (ii) grasping the specific needs of agro-food industry of the ER. Interviews are anonyms and the point of views of interviewees are reported in storytelling manners. Afterwards, benchmarking analyses on whether the I4.0 potentialities fit in with agro-food industry requirements and need is carried out.

Secondly, the DMI4.0 architecture is provided. First, the framework for gathering data is introduced. Tools and methods for elaborating data and achieving the needed information are described. Two tools are introduced: the 'House of Digitalization' (HoD), and the SWOT for industry, namely the 'SWOT4i'. The former tool follows the framework of the 'House of Quality' (Hauser & Clausing, 1988) of the 'Quality Function Deployment' (QFD) (Akao & King, 1990). QFD is a structured methodology for a structured identification and analysis of customer needs, for translating them into technical specifications quantitatively judged. The aim is at avoiding distortion of customer expectations from the product through the company's functions. QFD is used to convert customer needs into measurable quality characteristics towards the expected improvement of the product (Akao & King, 1990). HoD is here used for mapping how companies are approaching the industry r/evolution expressed by whether or not they adopt available cutting-edge technologies of I4.0, similarly as HoQ express whether or not companies face the customers' requirement when they develop a new product. The latter tool uses the 'Streght-Weakness-Opportunity-Threat (SWOT)' framework, for elaborating data gathered and then providing the DMI4.0 that assess the maturity level of systems. For a detailed description of the SWOT framework, the reader may wish to refer to Fifield (2012), Johnson et al. (2009), Kotler (2009), McDonald (1992) Palmer and Worthington (1992) and Wilson and Gilligan (2012). In this thesis the SWOT framework is adopted for developing a quantitative SWOT analysis for company evolution towards industry r/evolution, namely the SWOT for industry (SWOT4i). Then, the DMI4.0 for defining a development roadmap is discussed.

The rest of the section is devoted to presenting results of a practical survey of the agro-food industry of the Parma area, officially recognized as 'Creative UNESCO City for Gastronomy' and 'capital' of the ER

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[82] Source: AGRIFOOD.TECH. Visit: https://www.agrifood.tech/osservatori/lagrifood-italiano-e-sempre-piu-digitale-cresce-del-22-e-arriva-a-450-milioni/. Last access: 2020.09.03

[83] Source: Emilia-Romagna official site. Visit: https://www.regione.emilia-romagna.it/notizie/2019/marzo/emilia-romagna-tra-i-paesi-leader-per-lagroalimentare-oltre-176-milioni-per-innovazione-ricerca-e-sviluppo-e-441-progetti-finanziati. Last access: 2020.09.03

'food valley' since the excellence of its products[84]. Three SCs are here investigated, namely (i) animal preserves (i.e. cold meats industry), (ii) vegetable preserves (i.e. canned vegetable industry), (iii) dairy sector. Finally, discussion of results and conclusions are addressed. A concept map of the methodology developed is provided in Figure 4.6.

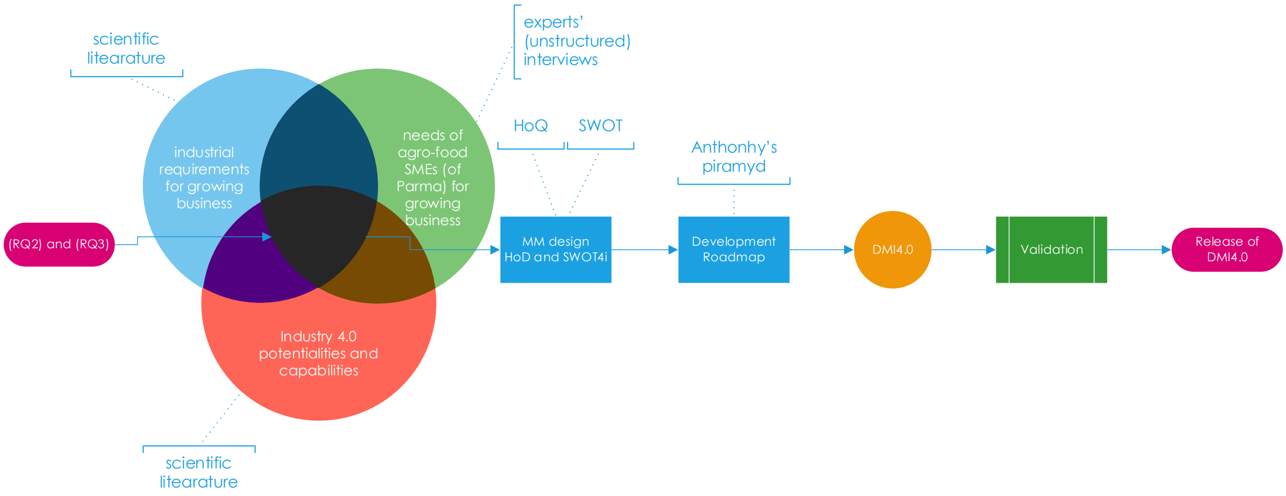

Figure 4.6. Concept map of research methodology for designing the DMI4.0

Methodology is described as framework in which stages subsequently flow. Materials and methods used in each stage are represented by text annotation in blue-colored font. Point of departure and end of the framework are represented with magenta-colored ovals. Blu boxes represent a process for defining outputs. Framed green box depicts a sub-process described apart, as it is a standalone framework adopting an own methodology. It relates to the validation of the model which is described in next Figure 4.7, which adopt the same graphic rules.

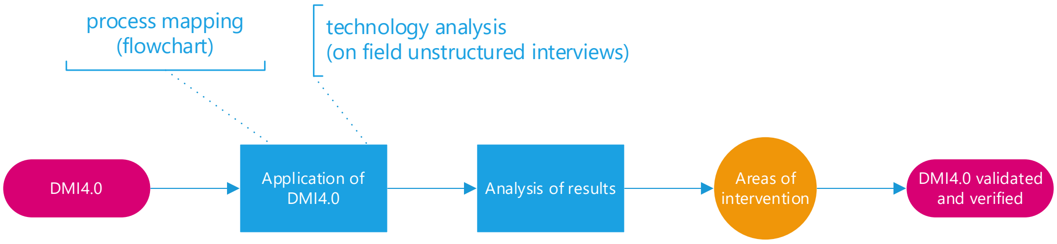

Figure 4.7. Validation process for the DMI4.0

4.4.2 *Benchmarking the I4.0 potentiality with the international and local industrial needs*

4.4.2.1 *A scientific perspective on business and production systems*

It is well-proven in scientific literature (e.g. Moeuf et al., 2018; Rüßmann et al., 2015; Günther Schuh et al., 2017), and it has also been recalled in this thesis, that the fourth industrial revolution of I4.0 demands new company' knowledges and personnel' competencies, leading to eventual new business and company organization: this new organization is driven by the evolution of technologies, especially digitalization technologies (via operational technologies and mechatronic devices) and ICTs (promoting an even increasing pushed use of the web). If on the one hand, disruptive technologies are leading the way, on the other hand they are disruptive not in the sense that 'technology availabilities' are changing, rather

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[84] Source: Ansa. Visit: https://www.ansa.it/emiliaromagna/notizie/speciali/2017/10/10/parma-cuore-della-food-valley-dellemilia-romagna_4de34e52-8a55-47aa-9891-da595c159f12.html. Last access: 2020.09.03

than the 'technology adoption' is growing and evolving (J. Lee, Bagheri, et al., 2015). In this way, businesses have to face same issues faced before the fourth industrial revolution too, i.e. they must adapt themselves to the so-called megatrends (Naisbitt, 1982) by pushing on sustainability, flexibility, and efficiency, leading to the ability to rapidly respond to changes in the surrounding environment (Adolph, Tisch, & Metternich, 2014).

In particular, with respect to the manufacturing environment, production systems can be generally characterized by means of the 'Polylemma of Production', thus describing their businesses through two main trade-offs (Brecher et al., 2012): (i) scale-scope economies, and (ii) value-production orientations. The former concerns the product, the latter is about the process (Brettel et al., 2014). Lots of studies have dealt with the identification of requirements of manufacturing industrial systems to balance and hence to solve the polylemma trade-offs. Among these, studies of Damm et al. (2010), Einsiedler (2013), and Vyatkin et al. (2007) can be interpreted as follows:

- With respect to the 'Scale-Scope' dilemma: it is possible to solve this trade-off pushing on shorter product lifecycles, i.e. (i) making fast the new product developments, and (ii) making flexible the production systems.
- With respect to the 'Value-Production' dilemma: core element to solve this trade-off is the data that allow (i) H2M interactions, and (ii) to gain information and knowledge by acquiring and processing it.

It has been demonstrated that these requirements can be satisfied by pushing on efficiency and flexibility (Günthner & Ten Hompel, 2010), through (i) decentralization (Spath et al., 2013) and (ii) capability of tracking the commodity flows and the information flows among business partners (i.e. active and passive cycles) (Robert, Janek, & Egon, 2012). Figure 4.8 recaps all considerations above in a nutshell.

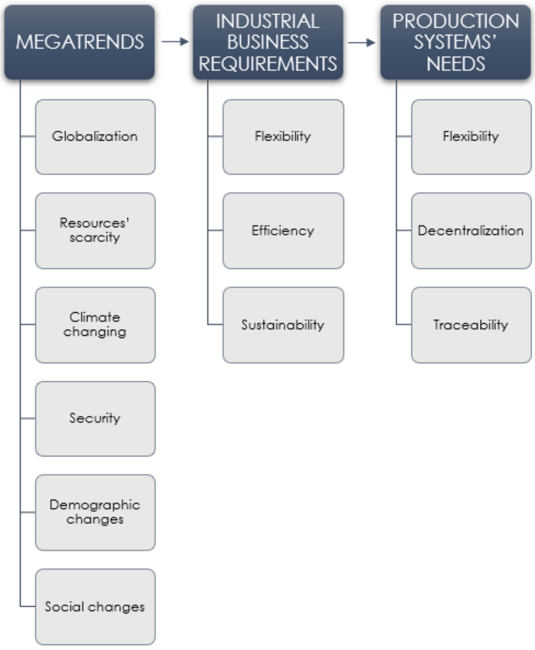

Figure 4.8. From the megatrends to the industrial requirements and needs

4.4.2.2 Investigating the ER' SMEs businesses: a case study of the food valley district

The centrality of the agro-food industry in the whole ER region has been previously introduced. This industry is nonetheless central in the industrial economy of the specific Parma district worldwide known as the 'food valley', which extends from Parma city to the mountains of the Tuscan-Emilian Apennines.

A survey by the UPI – Unione Parmense degli Industriali, within the project "*Individuazione delle soluzioni tecnologiche abilitanti e modeling delle competenze richieste nella filiera alimentare della provincia di Parma*" stated that focal firms of the industry (namely, the goods producers) amount to 1,210 enterprises and the insutry employees more than 14,000 people, having a whole annual turnover of €7,600 million. Meat-processing industries and dairy industries employ more than half of the people (i.e. 7500 people). Among other industries, vegetable preserves industry (i.e. canned vegetable industry) and the pasta and bakery industry stand out. If first two sectors are suitable to be surveyed, since their clear importance to the local economy, a consideration raises about the other two sectors. The enterprises of the pasta and bakery sector are of two different nature: pasta producers are generally LEs producing goods for the large-scale distribution, while bakery industry is mainly characterized by craft industries and even micro-enterprises. Thus, in this study focus is on three typical industries of the area, namely (i) cold meat industry, (ii) canned vegetable industry, and (iii) dairy industry. The core business of these focal agro-food sectors is providing customers with an excellent product, as the 'Parmigiano Reggiano' cheese and the 'Prosciutto Crudo di Parma' ham. They both are registered with the DOP trademark of the European Community and are produced according to rigorous regulations of the respective Consortia[85] [86]. Just a mention to the lexicon adopted in this thesis. All these enterprises belong to the manufacturing and processing industries as classified in Chapter 1, hence both terms 'manufacturing' and 'processing' can be used interchangeably when transformations of goods are described, although in this chapter term 'processing' is preferred because better recalling the transformations process. Moreover, when the whole industrial scenario is discussed, term 'industry' is adopted; whereas, when the focus is on one of its branches, the term 'sector' is preferred. For instance, the agro-food industry identifies all three SCs, an agro-food sector refers to just one of these.

These sectors have specialized 'satellite business' of machinery and plant manufacturers, which as a whole is composed of more than 600 companies employing 8,600 people, and whose know-how is internationally recognized, since they gain their turnover for more than 50% by exports worldwide (i.e. €1,250 million out of total €2,200 million). These players of the SC have been involved with the aim of gaining knowledges about the focal firms of the agro-food industry. Again, a mention to the lexicon adopted is judged useful. The term 'focal firm' is used according to the SC standard for identifying the central player of the SC with which the end product is identified. These players are hence also named 'goods producers'. For distinguishing these players from the manufacturer of machineries, equipment, and plants, and for the sake of conciseness, the second type of player is named 'systems engineering manufacturer'. The reason why systems engineering manufacturer have been surveyed for achieving knowledge of the industry is manifold. Firstly, technologies are central in the development of businesses, and the more they are innovative, the more they are core to letting business grow (Srinivasan, Lilien, & Rangaswamy, 2002). For instance, technologies have been discussed as real triggers to the fourth industrial revolution so far, and they are generally accepted as triggers of previous revolutions too. Secondly, by surveying the business-to-business (B2B) systems engineering manufacturers, it has been possible to build a best-in-class set of technologies that leads to way towards ultimate technology opportunities. Thirdly, systems engineering manufacturers have a 'neutral' standpoints of what it is important to supporting operations and business intelligence, namely individual (i) technology-sets and (ii) processes may depend on the specific goods producers and its business orientations (Bertolini,

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[85] Visit: https://www.parmigianoreggiano.com/

[86] Visit: https://www.prosciuttodiparma.com/en/home-page/

Esposito, & Romagnoli, 2020). Nonetheless, B2B systems engineering manufacturers have a very close relationship with the goods producers since the criticality of the industry and of the end product. Furthermore, they do business with customers of different nature, each with their own needs and requirements. These aspects mean that they have a general overview of the complexity and needs of the industry in which they operate. Contractors and third part manufacturers (3PMs) are not involved in the survey since their point of views directly flows in the perspective of the surveyed SC players.

Survey has been carried out in the form of unstructured interviews. For the description of the enterprises operating in the food valley, this thesis sticks to the classification of Williamson (1975), who identifies two forms:

- U-Form, i.e. the simplest form of unitary form of polyfunctional enterprises. The U-form is a business structure in which a single department manages strategies and makes decisions, while 'specialized units', grouped together according to similarity of tasks, and works complementary to each other. The U-form corresponds to the process-focused organizational form (Qian, Roland, & Xu, 2006).
- M-Form, i.e. the multidivisional enterprises. It is an organizational structure in which a firm is divided into divisions as 'self-contained units' in which task are grouped together according to their complementarity. Divisions have their own unitary structures and (partial) autonomy (Qian et al., 2006). The firm is essentially divided into corporate entities with each being responsible for its mansion (Chandler, 1990). The M-form corresponds to the product-focused organizational form (Qian et al., 2006)

The specific differences are here not considered, since it goes beyond the focus of this thesis. It is only stressed here that U-Form structures group individual skills and company functions according to the inputs to their work, while M-form groups them according to both inputs to the work to do and the outputs to achieve. In a nutshell, multidivisional structures are set for the specialization of the staff.

In the following, results of the survey are presented. The survey is driven by an agenda in two points:

- Providing and overview of machineries used in the SC by the producers of goods and solutions supplied by systems engineering manufacturers: this point wants to depict the level of technology complexity of the process, as well as future perspective for the agro-food industry and their sectors. The full description of processes and technologies adopted will be provided in the next section in which the digital maturity level of companies will be obtained according to the possibility of digitalizing the manufacturing process.
- Taking systems engineering manufacturers' perspectives on existing gaps in goods producers' adoption of innovative technologies to meet new market demands.

Evidence from the interviews is tracked in narrative form since they were not recorded nor registered in rigorous way. Names of companies are omitted for confidentiality reasons.

First, these aspects are discussed apart according to the SC investigated. Then, conclusions are addressed.

Cold meat industry

Systems engineering manufacturers of this agro-food sector are typically SMEs sited in the pre-hill area of the Parma Apennines. Position is strategic for better serving the goods producers, mainly ham factories, that are here located. Systems engineering manufacturers are mainly M-form enterprises, and few manufacturers still adopting U-form strategies are evolving towards the M-form. This aspect mainly descends from the fact that services to provide to the goods producers are becoming even more central in manufacturers' BMs, to the extent that cold-room equipment manufacturers and installers are switching to service-centered businesses, providing controls tools and data-storage services beyond manufacturing equipment and machineries, and installing them. In fact, in the cold meat industry there are two systems engineering manufacturers, namely (i) machinery manufacturers and (ii) cold room equipment manufacturers. Assets supplied cover the whole process, from the equipment for handling raw material feeding the transformation process, to machineries supporting personnel in the quality control of end products, through the cold rooms and related devices for the aging of goods. Both typology of manufacturers uses specialists for ICT infrastructures and electrical systems of production lines. This survey has involved both (i) a machinery manufacturer, and (ii) a cold room equipment manufacturer.

As emerged from the interviews, service-oriented BMs are raising since it is a segment of business not yet fully developed. For the cold room equipment manufacturers, this comes from the possibility of networking the process.

> *The possibility of networking the aging phase of hams, by controlling it by remote, increasingly suggests providing customer assistance, by monitoring the aging process and providing precise information on deviations from optimal conditions but also historical data from which obtaining information for forecasting future aging processes and goods quality.*

An even increasing service-oriented portion of business is raising for machinery manufacturers too.

> *Production is not really stressed, namely a production line processes on average 700 pieces per hour. Nevertheless, the production lines are continuous, thus goods producers often neglect routine maintenance. Hence, this makes room for maintenance service divisions. Furthermore, preventive maintenance gained attention from the goods producers, and machineries are even more equipped with sensors and devices tracking the state of systems and possible failures. But this is still in an infancy stage, and only few manufacturers have asked to systematically install these systems.*

Nonetheless, business partnerships among these manufacturers and producers are successful since most plants are customized to fit in with specific processes or needs of the producers.

Criticalities of the sector have been highlighted as follows:

- Traceability of raw material is a key factor for ham productions. However, traceability relates to the meats rather than the pigs and its genealogy. Furthermore, regulations set rules for the animal farming, but they do not regulate genetic screening for both male and female animals. These aspects hinder to link the product excellence with the raw material excellence.
- It is still difficult to differentiate quality and non-quality productions, probably because of inability of the consortium to monitor production stages and process phases.

Canned vegetable industry

Systems engineering manufacturing for the canned vegetable industry are mainly corporate enterprises (often publicly traded) supplying turnkey plants as well as plant parts. Here again, private contractors supply electrical systems and ICT infrastructures. Two systems engineering manufacturer have been involved in the survey. They are M-form companies which aim both local and international SMEs and LEs producers of seasonal vegetable canned food, mainly tomato sauce producers.

As it emerges from the survey, the manufacturing process is well-established, and it does not need innovative or disruptive technologies for producing the product (i.e. direct technologies). The process is affected by high seasonality of raw materials (mainly tomatoes): if this allows to schedule standard maintenance during downtimes, on the other hand when the plants is working it needs reliability and effectiveness. For all these reasons, goods producers increasingly ask for machineries and equipment that make the process:

- Working 24/7 and with as less as possible stops.
- Rapidly interchangeable, namely requiring as less as possible time for setting up next processing phase.
- Near-real time in-plant traceability of goods for scheduling activities with respect to real productivity of the plant and monitoring costs for the production batches.

On the contrary, machineries and equipment have been already digitalized and integrated during recent years. Thus, technologies supporting the processing of products (i.e. indirect technologies) are continuously evolving towards the provisioning of information in the form of services to divisions and production business intelligence. This aspect is becoming central because of the increasing centrality of information to improve the process and monitoring the plant efficiency.

> *If systems control is very developed, e.g. for monitoring state parameter of machineries and equipment, monitoring process performance can help to better maintain machineries and equipment, also during the uptime (i.e. when the plant work): maintenance is crucial since different goods and products are processed, and they wear equipment in a way that is difficult to predict. As a result, both efficiency of the process and financial sustainability of the business verifies improvement.*

Dairy industry

Two kinds of systems engineering manufacturers supply machinery and equipment for producing dairy products. The former relates to small enterprises that manufacture assets for dairy farms, and small enterprises. They supply assets for the whole production line, and these assets are low-tech products. The latter relates to medium-large systems engineering manufacturers, that provides LEs of the dairy processing industry with turnkey plants often composed of machineries and equipment manufactured by small and medium 3PMs. Since former typology better complies with the purposes of the research, and furthermore since these manufacturers are often 3PMs involved in the latter scenario, the research has investigated these players. They typically are U-form enterprises, that have gained a specialized know-how through long-term partnership with goods producers. Assets supplied are machineries and equipment for both goods producing and cheese aging (i.e. ‘Parmigiano Reggiano’ cheese). Differently from ham production, aging does not need cold rooms. This means that a single manufacturer can supply assets for orchestrating the whole production line. However, due to the producers’ demand a consideration arises:

> *Since the target mainly is pretty-craft industries, machinery and equipment manufacturers struggle to improve the technology level of solution and to upgrade assets towards digitalization and automation.*

In fact, automation technologies have only been spreading for a few years. Beyond the target’ demand, the craft nature of the process, and its characteristics (namely, batch process and very different tasks) seem prevent further process automations from raising.

> *Only systems control for product quality seems to attract the goods producers to digitalization and automation. It sounds fuzzy that just some producers are interesting to the ability of monitoring capability and efficiency of their plant.*

Finally, a common interest of all the players within the SC towards building a VN seems to be still missing.

> *They seem to be passive in accepting regulation of the Consortium, as they do not have the ability of regulate and protect themselves as active players working together in synergic way.*

4.4.2.3 Results

In chapter 2 it has been showed the role of I4.0 as engine powering sustainability, flexibility, and efficiency, as well as decentralization, and value-creation network, exploiting ICTs for digitalization and networking, and new principles as the total integration of systems. In this chapter, a further analysis on evolution of business and operations management has analyzed the increasing needs and requirements of international industries, namely (i) flexibility, efficiency, and sustainability of business paradigms, and (ii) decentralization on intelligences and traceability of products and processes. That sounds as I4.0 is not the 'cause' of the industry r/evolution, rather than it is the 'effect' addressing how to face recent requisites of industrial businesses and production systems through the exploitation of digitalization and communication technologies, towards the total integration of systems.

The second part of this section has been devoted to analyzing specific needs and directions of the SMEs of the ER region, especially those belonging to the food valley of the Parma area. As it has emerged from a survey involving six systems engineering manufacturers of food processing industry, most goods producers of the industry are SMEs, whose productions are characterized by partially industrialized processes. Core of their business is the quality of their products, although attention is recently turned to efficiency of processes and, more in general, of the SC. All sectors share some specific needs to which producers have to adapt, and emerging market' demands present some challenges to face. In the following, they are recalled.

Traceability of goods feeding the process seems to be a core element of all sectors. It can add high-quality of raw material to high-quality of process, allowing to produce certified product aiming at excellence. This would also push collaboration and synergy among business partners. The focus on process towards its excellence is increasingly leading the approach of goods producers to purchasing services more than just machineries and equipment. Required services relates to both expanding the capacities of technologies (e.g. by adding cloud storage service for data generated by equipment) as well as intelligence for monitoring and optimizing performances.

The increasing needs for traceability and performance monitoring as emphasis on services to be provided, could be linked to general requirements of industries and business. In fact, these needs stick close to five drivers previously identified, namely (i) flexibility, (ii) efficiency, (iii) sustainability, (iv) decentralization, and (v) traceability. For instance, for the goods producers the increasing stress on services relates to added value to buy from the partners, hence it is linked to the efficiency of the process rather than the servitization of the end products. Nonetheless, it is still a bit fuzzy relating the 'service' concept to food products. Hence the increasing focus on servitization refers to the increasing focus on systems efficiency and decentralization of intelligence, for instance by networking assets and providing factory units with the suitable analytics for decision-making. As well as pushing on traceability, goods producers can pursue efficiency and sustainability of businesses and processes, in such an 'open environment' in which resources are not unfairly exploited and SC gains visibility.

In Table 4.6 there is an attempt to match results from the field survey and the analysis of literature on of I4.0. Two umbrella terms are used to cluster industrial needs of the agro-food chain of the Parma district as emerged from the survey, namely 'service-oriented partnerships' and 'transparency'. Umbrella terms represents the directions currently pursued. Clustered needs represent the expected results of the industry evolution. Concerning the industrial r/evolution it has been largely debated in this thesis that, among other requirements and needs, (i) vertical and end-to-end integration allow to cope with industrial operations efficiency and intelligence decentralization, as well as (ii) horizontal integration also cope with tracking and tracing goods, operations, and practices, and business sustainability.

Table 4.6 - Matching between I4.0 potentialities and agro-food industry towards international perspective of growth

Industry	**Service-oriented partnerships**	**Traceability**	**Integration**
Cold Meat	Efficiency	Traceability, Sustainability	Vertical, Horizontal
Canned Vegetable	Efficiency, Decentralization		Vertical, End-to-End
Dairy	Efficiency	Traceability, Sustainability	Vertical, Horizontal

4.4.3 Technology drivers for maturity analysis

The increasing need for 'transparency' of the SC, as well as for efficiency and decentralization, require a suitable technology stack. The following analysis of technology available for fostering I4.0 is retrieved from Brettel et al. (2014) and coherently sticks to total integration of systems.

Horizontal Integration

The core element transforming manufacturing companies into integrated networks is the availability of data through the entire network, allowing companies to share their core competencies towards common business and production strategies for a global optimization of the system. Uniting core competencies is an approach already debated in literature. For instance Christopher (2000) have discussed the need of companies for focusing on their core competencies and outsourcing other activities to business partners in the network, towards business and production strategies pursuing agility. Thus, the capability of sharing data eventually leads also to (i) mass customization, (ii) financial sustainability of business (especially for SMEs), (iii) short product development and life cycle, and (iv) flexibility (Brettel et al., 2014).

The increasing need for sharing data requires to communicate and coordinate activities across the network as an efficient whole system. Advancements of ICTs allow to continuously capture data that will be later processed. Reliable and even more cheaper technologies such as RFID and more in general sensors allow data to be accessible through networks. The infrastructure that makes possible sharing this data is the Internet, of course.

(Vertical and) End-to-End Engineering Integration

Integrated engineering across the entire value chain pursues optimization of processes through advanced methods of communication and virtualization. Optimization refers to the capability of (i) accessing to and (ii) controlling real-time information regardless which particular factory or company is generating information. CPSs foster virtualization of business processes and engineering workflows and services (Kagermann et al., 2013). Of course, sharing information requires infrastructures enabling companies to integrate their data among systems, as well as standards for data-transfer and utilization (Schulzet, 2011[87]; Tao et al., 2011), but also it can exploit virtual reality for illustrating information for effective collaborations. Finally, the capability of business partners to effectively collaborate in real time for intervening in case of changing conditions of processes, fosters manufacturing companies to provide value-added services, with the aim of differentiating themselves on the market in addition to high product

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[87] Schulzet Wolfgang al. (2011), Virtuelle Produktionssysteme, "Integrative Produktionstechnik für Hochlohnländer", Brecher Christian (Hrsg.), Berlin, Heidelberg, Springer, pp. 256-464. Retrieved in: Brettel et al. (2014)

quality assured. Embedded Systems of smart machines push on new remote maintenance concepts (Kagermann et al., 2013).

As a result, two main categories arise that can cluster technologies promoting total integration of I4.0: (i) Virtualization Technologies, and (ii) Communication Technologies. 'Virtualization' of systems refers to a new form of adding value in the manufacturing and processing phases, as well as in the business practices (e.g. the receivable and payable cycles), by means of data and information (Brettel et al., 2014). 'Networking' systems is strictly linked to the ability of producing data, in fact it means sharing data and information, both inside and outside the company boundaries, for adding value to the process and hence to the product (Brettel et al., 2014). Technologies that can be identified in the cluster are then listed in Table 4.7, as a result of the analysis of Brettel et al. (2014) and as evidences from Chapter 2 of this thesis.

Table 4.7 - Clusters of integration technologies towards developing traditional systems into I4.0 systems

Technology cluster	**Technology Exploitation**	**Suitable technologies (some examples)**
Virtualization techs	Data capturing and elaboration of information (vertical and end-to-end integration)	(smart) sensors, smart machines and embedded systems, RFID, virtual realities, CPS, DT, simulations, BDA, M2M, M2H
Communication techs	Fostering network of systems (horizontal integration)	Internet and Internet standards (e.g. Wi-Fi, 5G), data standards and communication protocols, blockchain

Both technology clusters strictly relate to capability of produce data and then to the 'digitalization' of systems: in fact, according to the glossary adopted in this thesis, digitalization refers to the capability of systems of producing digitized information and using them to create value in new ways, and then to benefit from this. In the following, the term 'system' is meant as combination of technologies, operations, people involved, and related business practices. Whereas, since the direct connection between digitalization and integration, the terms will be used interchangeably with little nuances more linguistic than conceptual.

4.4.4 The DMI4.0

The MM proposed in this study is structured as a three-step framework for calculating the maturity level of companies and more in general of industrial systems, through the graphical tool DMI4.0 previously introduced. The framework is represented in Figure 4.9, in which the convention already adopted in Figure 4.6 and Figure 4.7 is adopted, and it is described in the following.

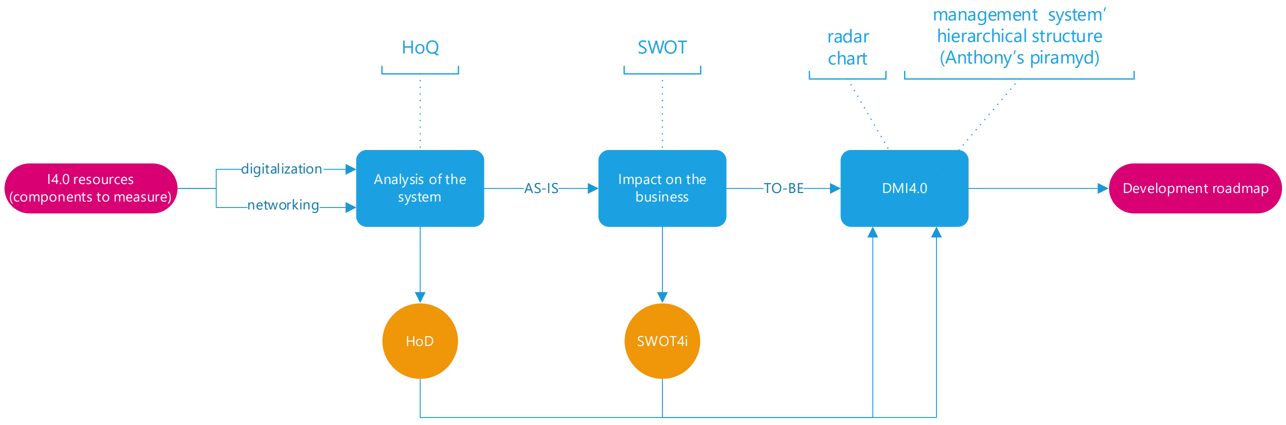


Figure 4.9. Three-step framework design of the DMI4.0

First step concerns an analysis of the system to be surveyed with respect to (i) integration level of its processes, (ii) how assets are inserted in networked infrastructures, and (iii) how these infrastructures are connected with others belonging to the SC. The tool designed for carrying out this analysis is the HoD. HoD exploits the HoQ design and computations rules as in Braglia et al. (2018). A complete description of the HoQ model is here missed, and this thesis suggests to refers to Hauser and Clausing (1988) for a comprehensive description. The proposed HoD differs very little from the HoQ adopted from Braglia et al. (2018) and main differences relate, of course, to the different objectives of the tools: while Braglia et al. (2018) use the HoQ for the risk assessment due to human error of the workers during operations, in this case is used for analyzing how much the process is digitalized, what integration technologies are used, and if the product lifecycle is shared among business partners. For instance, in the 'House of Safety' (Braglia et al., 2018) 'room #5' definitely vanishes, while as it is explained in the following, it is fundamental for the development roadmap characterization.

Second step concerns the elaboration of quantitative data calculated by HoD tool. It aims (i) to provide the impact of digitalization and integration technologies on business AS-IS and (ii) to define future perspective TO-BE. The tool designed is the SWOT4i matrix, which exploits the design of the well-known SWOT matrix of the SWOT framework. The approach followed in this thesis for the SWOT4i is quantitatively, although conforming to the SWOT original design. In this case too, goals are different of course, i.e. SWOT analysis is usually performed to highlights why to plan and to fund business cases, and difficulties are supposed to be faced. SWOT4i is aimed to enlighten where business is weak with respect to I4.0 technology and business r/evolution, and how to evolve through further digitalization and integration of systems.

Based on the SWOT4i analysis, graphics are elaborated for providing the digital maturity level of the system to survey, and relative technologies and principles still missed. As a result, business intervention areas are defined. Business intervention areas are defined as (i) Strategical area, (ii) Tactical area, and (iii) Operations area, according to the pyramidal classification for management system organization of Anthony (1965):

- Operational level: it concerns operations, and it entails design activities, production activities, and dealing and service supplies in general. It pursues short-term objectives.
- Tactical level: it concerns tactics, namely it deals with managing decisions coming from strategies, towards their implementation at the Operational level. It pursues middle-term objectives.
- Strategical level: it concerns strategies, namely it deals with making decisions towards directions to follow, hence pursuing long-term objectives.

Graphs of SWOT4i analysis are elaborated in radar-chart manner.

It is noted the whole MM calculating the maturity level of the system is named DMI4.0, and the same term is used as a synecdoche for describing the end step of the framework addressing results.

4.4.5 The House of Digitalization HoD

HoD is a graphical tool. It consists of 8 'rooms', according to the lexicon generally adopted for the HoQ. Each room is devoted to technical analyses of all the parts of the whole system. Analyses are of different nature and are here introduced briefly for a better comprehension of the model.

Firstly, an analysis of the AS-IS configuration, namely process design and technologies adopted by the specific reality is carried out.

Secondly, relevant I4.0 components exploited or missed by the system are analyzed. A main driver is identified, as it descends from the analysis developed in the previous subsection: the digitalization. The digitalization level is considered the yardstick for measuring both the integration level AS-IS and the possible TO-BE. This second step of analysis is translated quantitatively introducing weights and indexes that express the compliance of the system with I4.0 characteristics and principles.

Finally, weights and indexes are combined following calculation rules of the HoQ for a quantitative analysis of integration level, with respect to the potential one of the best-in-class benchmarks.

The HoD is described room by room in the followings. First, the framework and computations rules are introduced. Then, how to fill in each room with data entries and the meanings of each index is provided.

Room #1, Room #2, and Room #3: mapping the process and its potentialities

'Room #1' collects all technologies available on the market for manufacturing and processing goods. Technologies surveyed are those used for manufacturing activities and are here named 'direct technologies'. At the end of the survey, N technologies are listed in the room.

The manufacturing process, as executed by the firm investigated, is characterized in 'Room #2'. as a sequence of M phases.

An 'anteroom' between rooms #1 and next #3 is devoted to expressing opinion about how much the technologies owned by the company are digitalized, namely they allow to gather and share data from the process phases that they realize, towards the integration of systems. This is expressed through the 'digitalization weight' d_{w_i} for each technology i. The scale of judgement follows the classic approach of the HoQ Braglia et al. (2018), namely a 1-3-9 scale whose values in the HoD have the following meanings:

- Value 1 indicates low digitalization of the technology i. Typically, data are collected manually and then are digitized by means of information databases or spreadsheets.
- Value 3 indicates medium digitalization of the technology i. Typically, digitalization is limited to setting and controlling processing parameters, for instance using user interface for programming CNC machines, as well as storing data gathered from the process, for instance by .csv document. Data are somehow generated automatically and then are stored and accessed when and whether necessary, and then elaborated for sharing them with stakeholders.
- Value 9 indicates high digitalization of the technology i. Typically, the technology is integrated in the MES or in the ERP, as well as in the CRM, in EDI systems and other suitable platforms (also self-designed) for increased and real-time transparency of information.

Of course, if the firm does not own a specific technology, 0 or *null* value is inserted. Otherwise, if the technology is outsourced, it is judged coherently with the 1-3-9 scale the capability of receiving data from the supplier that realize the related process phases.

'Room #3' is the 'Relationship Matrix' between technologies and digitalization of process phases. It expresses how much the j^{th} process phase realized by the firm would be integrated if it adopts a best-in-class technology of i^{th} typology. In each box b_{ij} the impact of the technology adoption on the system digitalization is quantitatively inserted. The index is named 'Integration Capability weight' IC_w for the capability of digitalization of further integrate systems. Values range according to the same 1-3-9 scale previously introduced. Otherwise, if the technology i cannot digitalize the process phase, then IC_w for box b_{ij} is 0 as well as $null$ value.

How is it possible to fill Rooms #1 - #3 in with data entries?

Room #1 collects all the typologies of direct technology available on the market for realizing each process phase. The list of direct technologies comes from surveys involving manufacturer of machineries, equipment, and plants. Typically, this list could be superabundant, meaning that not all i technologies available on the market are owned by the specific firm that wants to assess its maturity level towards I4.0. However, by describing the direct technologies that can realize all the processing phases, the state-of-the-art of the sector can be derived: ideally, a process realized by all these technologies is the most technology-based manufacturing and transformation process.

Room #2 needs to describe the manufacturing and transformation process as a sequence of j phases. Directly interviewing the firms can provide a thoroughly description of the process. Lots of systems engineering tools can be used for mapping the process as a specific sequence of phases to be translated in this room. Flow charts can help this way. However, it is described, it is fundamental to list all the phases of the process. On the contrary, order does not matter; however, it is opinion of who have designed the model and write this thesis that it helps to avoid neglecting to consider some phases.

In the ‘anteroom’ the analyst surveying maturity judge each technology owned by the firm. The firm can own all the technologies available on the market, identified in room #1, as well as just some out of all. The judgement descends from a description of these technologies and the way they are used provided by the same firm. Hence the analyst translates its judgement in suitable values of the 1-3-9 scale of HoQ,

Room #3 express the capability of technologies of digitalizing processes. This capability can refer to both the concurrently exploitation of technology add-ons, here named ‘indirect technology’, for gathering data and communicating them among manufacturing and business systems (e.g. RFID, smart sensors), as well as CPSs and embedded systems natively generating and networking data. Typically, the numerical values of IC_w in room #3 are assigned by the analyst as a synthesis of descriptions of all experts involved so far, namely the firms, and especially the systems engineering manufacturers since their knowledge of technologies, industry processes, and general industry environment.

A representation of rooms #1, #2, the ‘anteroom’, and room #3 is provided in Figure 4.10.

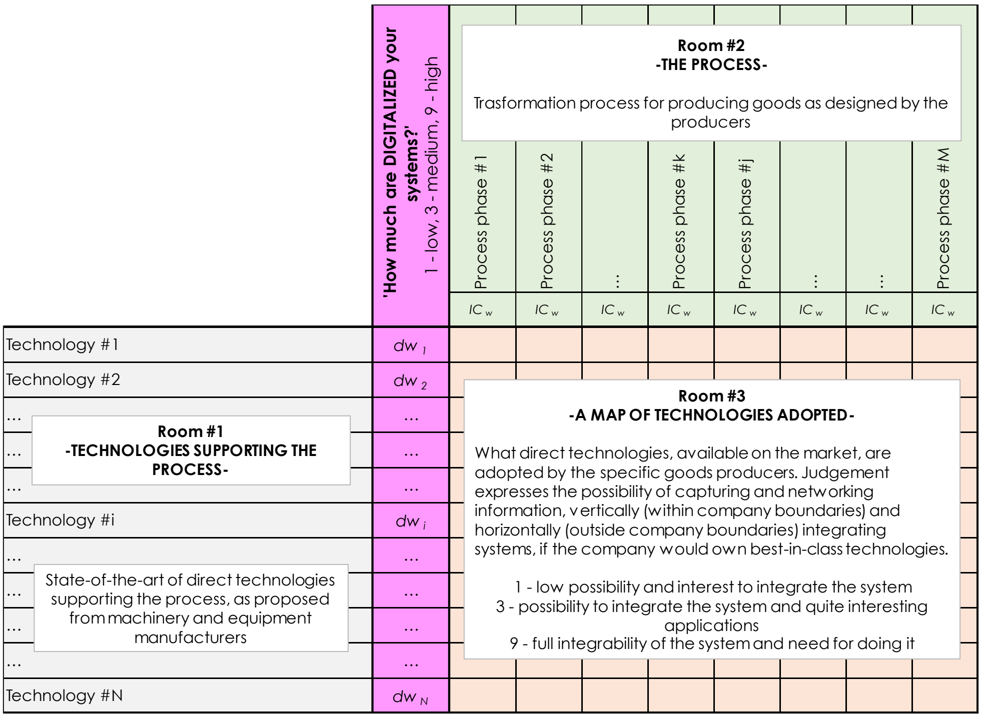


Figure 4.10. First three rooms and digitalization ‘anteroom’ of the HoD

Room #4 and room #5

In 'Room #4' is computed the 'Technology Incidence on integration' of each technology i, namely its overall impact on integration assessed on all process phases in which it is used. The technology is considered in the configuration owned by the firms investigated. This value is represented by the 'Factor of Technology Incidence on Integration' FTI and it is calculated as in (1).

$$FTI_i = \sum_{j=1}^{M} d_{w_i} * IC_{w_{ij}} \tag{1}$$

From equation (1) it is computed the normalized value $NFTI$ (2):

$$NFTI_i = \frac{\sum_{j=1}^{M} \overline{d_{w_i}} * \overline{IC_{w_{ij}}}}{N * M} \tag{2}$$

Where:

$\overline{d_{w_i}} = \frac{d_{w_i}}{H} =$ normalized digitalization weight for technology i

$\overline{IC_{w_{ij}}} = \frac{IC_{w_{ij}}}{H} =$ normalized Integration Capability weight for technology i

$H =$ maximum valued of the scale of judgement. In the scale adopted, $H = 9$

$N, M =$ number of technologies and process phases, respectively

Of course, due to the normalization, if all technologies concur at the most integration possible of the system, namely $IC_{w_{ij}} = 0\ \forall i, j$, and the firm owns the best-in-class technologies available on the market, namely $d_{w_i} = 9\ \forall i$, then $\sum_{i=1}^{N} NFTI_i = 1$.

In 'Room #5' is computed the 'Technology Potential for integrating systems' of best-in-class technologies, namely the overall impact on integration assessed on all process phases in which a technology i can be used. This value is represented by the 'Factor of Technology Potential on Integration' $FTPI$ and it is calculated as in (3).

$$FTPI_i = \sum_{j=1}^{M} IC_{w_{ij}} \tag{3}$$

From equation (3) it is computed the normalized value $NFTPI$ (4):

$$NFTPI_i = \sum_{j=1}^{M} \frac{\overline{IC_{w_{ij}}}}{N * M} \tag{4}$$

Also in this case due to the normalization, if all technologies concur at the most integration possible of the system, namely $IC_{w_{ij}} = 0\ \forall i, j$, then $\sum_{i=1}^{N} NFTPI_i = 1$.

Roles of computed indexes in the DMI4.0

The comparison between $NFTI$ and $NFTPI$ disclose gaps between the AS-IS integration of the system, and its possible integration to realize adopting the best-in-class technologies available on the market. The reader can directly note that the same does not apply to FTI and $FTPI$ because of different scale of measurement. They are represented in Figure 4.11.

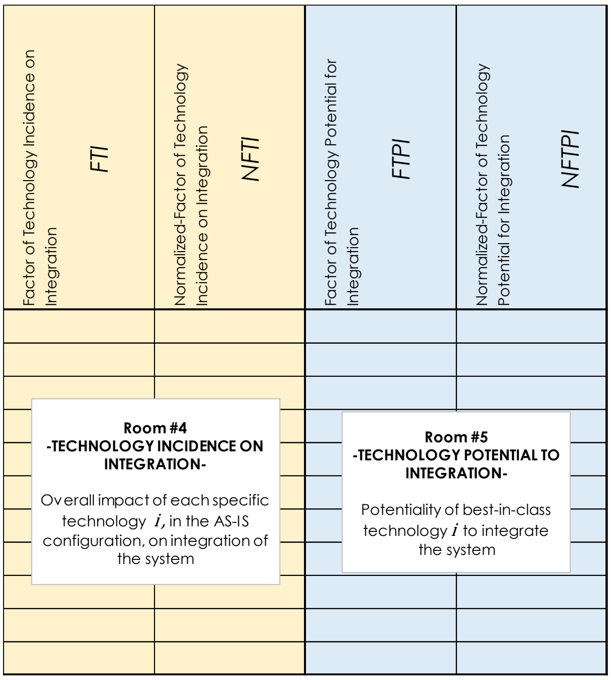
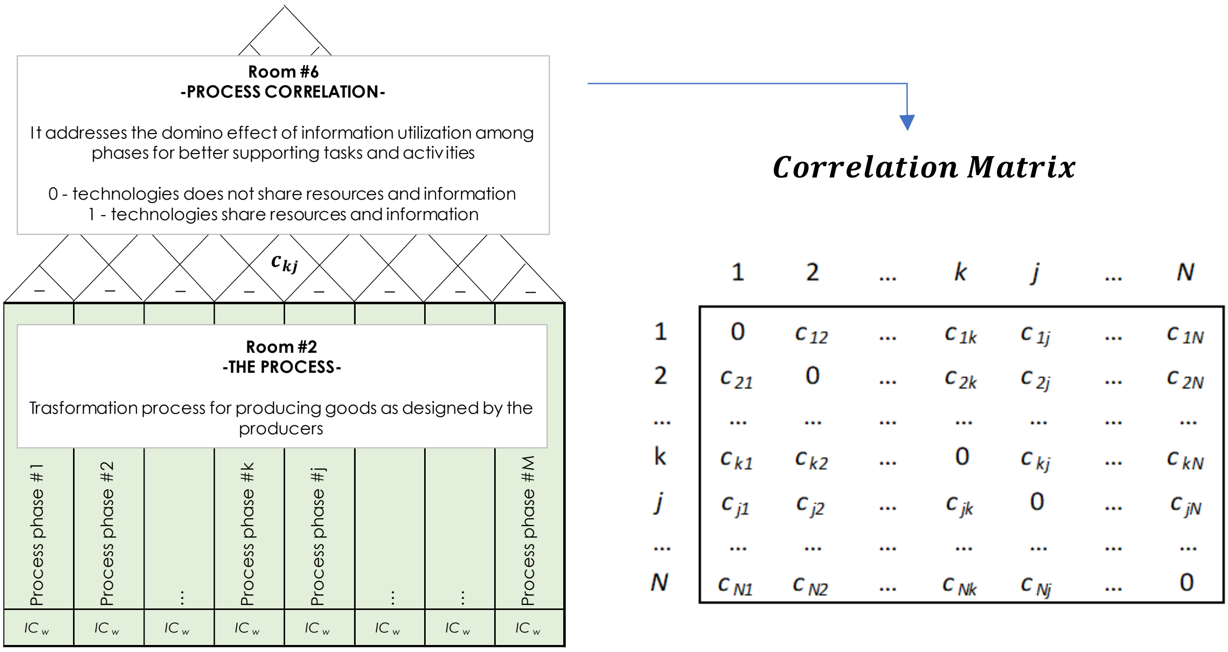


Figure 4.11. Room #4 and room #5 of the HoD

Room #6

In 'Room #6' it is evaluated to what extent process phases are complementary to each other, in terms of the benefits gained by the mutual interconnection. Correlation between pair of process phases k and j is represented by coefficient $c_{kj} = 1$ if one process is related to the other, either through series or parallel connection equally. Otherwise, $c_{kj} = 0$. Of course, if $k = j$ coefficient is null. Graphically, the correlation matrix is represented by the 'roof' of the house, namely a triangular matrix. For computation, a matrix MxM is built: the matrix is symmetrical, according to the HoQ design, namely $c_{kj} = c_{jk}$. Room #6 and the 'Correlation Matrix' are represented in Figure 4.12.



$$\begin{array}{c|ccccccc}
 & 1 & 2 & \dots & k & j & \dots & N \\
\hline
1 & 0 & c_{12} & \dots & c_{1k} & c_{1j} & \dots & c_{1N} \\
2 & c_{21} & 0 & \dots & c_{2k} & c_{2j} & \dots & c_{2N} \\
\dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\
k & c_{k1} & c_{k2} & \dots & 0 & c_{kj} & \dots & c_{kN} \\
j & c_{j1} & c_{j2} & \dots & c_{jk} & 0 & \dots & c_{jN} \\
\dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\
N & c_{N1} & c_{N2} & \dots & c_{Nk} & c_{Nj} & \dots & 0
\end{array}$$

(a) (b)

Figure 4.12. Room #6 of the HoD: (a) roof of the HoD and (b) related Correlation Matrix

Room #7 and Room #8

Room #7 and room #8 are devoted to the analysis of the AS-IS integration of the whole system, phase by phase.

Two indexes are calculated, namely the 'Potential Integration of the phase' PIP (5) and the 'Integration level of the phase' ILP (6) for each process phase j.

$$PIP_j = \sum_{i=1}^{N} IC_{w_{ij}} \qquad \forall j \in [1; M] \tag{5}$$

$$ILP_j = \sum_{i=1}^{N} d_{w_i} * IC_{w_{ij}} \qquad \forall j \in [1; M] \tag{6}$$

PIP and ILP expresses the integrability of each process phase adopting the best-in-class technologies available on the market, and the integration of the same process phase as it is realized in the current configuration by the firm.

The percentages of PIP and ILP, relative to the number of technologies involved in realizing the process phase, expresses the 'Integrability Index of the Phase' IIP (7) and the 'Phase Integration Index' PII (8) respectively:

$$IIP_j = \frac{PIP_j}{N_j^*} \qquad \forall j \in [1; M] \tag{7}$$

$$PII_j = \frac{ILP_j}{N_j^*} \qquad \forall j \in [1; M] \tag{8}$$

Where:

$N_j^* =$ number of technologies realizing the process phase j, $N_j^* \leq N \; \forall j$

In 'Room #8' firstly th 'Phase Complementarity' for each phase j is computed as in (9).

$$PC_j = \sum_{k=1, k \neq j}^{M} \left[c_{jk} * \sum_{i=1}^{N} d_{w_k} * IC_{w_{ik}} \right] \qquad \forall j \in [1; M] \tag{9}$$

Then is computed is relative values with respect to the number of technologies working concurrently, namely the 'Phase Complementarity Index' (10).

$$PCI_j = \frac{PC_j}{\sum_{k=1}^{M} c_{ik}} \qquad \forall j \in [1; M] \tag{10}$$

Finally, it is possible to calculate the 'System Integration Index' with respect to each single process phase j as in (11). The principle outlined by this index is that the more phases of the process are connected to each other by technologies, the more the whole process can gain efficiency and reliability, since activities are supposed to share information.

$$SII_j = PII_j + PCI_j = \frac{\sum_{i=1}^{N} d_{w_i} * IC_{w_{ij}}}{N_j} + \frac{\sum_{k=1,k \neq j}^{M} \left[c_{jk} * \sum_{i=1}^{N} d_{w_k} * IC_{w_{ik}} \right]}{\sum_{k=1}^{M} c_{ik}} \tag{11}$$

$$\forall j \in [1; M]$$

A representation of Room #7 and room #8 is provided in Figure 4.13.

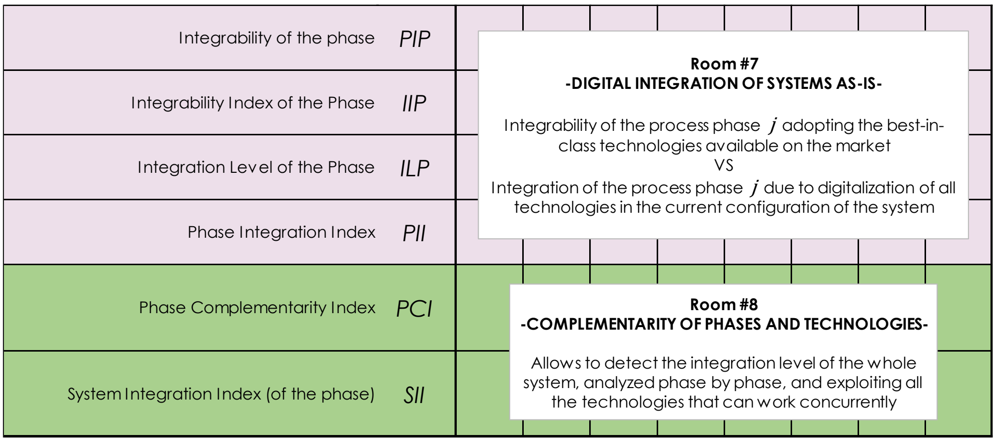


Figure 4.13. Room #7 and Room #8 of the HoD

4.4.6 The Smartification-Webification-integratiOn-Technology stack matrix for industry SWOT4i

The second step of the framework leverages a tool designed as the SWOT matrix for the SWOT analysis. As the SWOT matrix is a strategic planning technique used to help a person or organization to identify strengths, weaknesses, opportunities, and threats related to business competition or project planning[88], the SWOT4i is a tool for evaluating how much processes are digitalized towards the integration of systems, and consequently planning a development roadmap. The structure replicates the one used for the SWOT analysis, and the name also is a coherent acronym, hence the matrix is composed of 4 boxes each one filled in with suitable phases of the manufacturing process:

- Box 'S-martification': it relates to the exploitation of technologies for making 'intelligent' decision-making units, regardless the hierarchical level of management organization. Therefore, phases of the process that entail decision-making process are here considered. For instance, concerning the agro-food industry, phases related to the quality control are inserted in this box.
- Box 'W-ebification': it relates to phases of the process that allow to orchestrate the system based on data acquired and information elaborated. For instance, automated phases as well as those in which the system is controlled and then managed by remote are inserted in this box.
- Box 'integrati-O-n': it directly relates to process generating data and sharing information via suitable technologies. These phases are those that allow to gain knowledge of the state of the system towards the value-creation network leveraged by boxes S and W.
- Box 'Technology stack': it relates to phases of the process which are changing because of the use of disruptive technologies, and those that uses technologies capable of introductory change the 'way of doing things'. The way in which this room likes after survey is somehow related to the 'open-mind' attitude of the firm. For instance, sorting and picking systems managing the warehouse based on the quality control and customers' orders, respectively, can be inserted in this box.

Of course, relations between the boxes of the SWOT4i do exist, and a same process can be inserted in more than a single box. This way, the SWOT4i matrix shares some characteristics with the SWOT matrix, although the box S-W-O-T of the SWOT4i are arranged clockwise, differently from those of the SWOT analysis:

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[88] Source: SWOT Analysis: Discover New Opportunities, Manage and Eliminate Threats. Retrieved from: https://www.mindtools.com/pages/article/newTMC_05.htm. Last access: 2020.09.12

- Two vertical columns address the 'Helpful' and 'Harmful' sets of elements when facing the I4.0 transformation of the system: the 'S' and 'W' box represent the 'Helpful' transformation, since are related to system optimization, efficiency, and sustainability. The ''Harmful' transformation is represented by the 'T' and 'O' boxes since the firm and its SC can be still not technically and culturally ready for transforming itself and it needs a suitable accommodation for successful transformation.
- Two horizontal rows address the 'Internal' and 'External' set of elements, as well. They relate to phases of the process that can be directly controlled and managed, and phases of the process that involve 'external' business partners and then are only partly owned.

S-W-O-T boxes are arranged as in Figure 4.14. Phases, suitably related to the suited box, are listed in the row of each box. Each phase j brings its 'System Integration Index' SII_j and the relative 'Integrability Index of the Phase' IIP_j as computed in (7) and (11) respectively. Furthermore, the phase typology is classified according to the Anthony's pyramid (1965).

4.4.7 The DMI4.0: enlightening gaps for a development roadmap

The last step for stating the maturity of the systems towards I4.0 is the provision of suitable indexes simply recapping what has been calculated so far. The 'Digital Maturity Index' for each S-W-O-T box B is computed as in (12), where n is the number of phases relating to the box. Of course, $n \leq N$. Scale of representation adopt the Likert-scale, whose value ranges from 1 ('childish' system) to 5 (highly mature system). Values are rounded for matching second unit stepped of 0.5 point (e.g. 1.8 values 2, on the contrary 4.15 values 4).

$$DMI_B = \frac{\sum_{h=1}^{n} SII_{h,B}}{n} * 5 \qquad n \leq N \qquad (12)$$

Development roadmap consists of two steps and it refers to the approach developed by Günther Schuh et al. (2017):

1. First step entails balancing the radar, namely planning and realizing implementation projects that allows to shape the parallelogram as a regular rhombus. For this step, the comparison between the indexes $NFTI_i$ and $NFTPI_i$ discloses gaps between the possible integration level to achieve exploiting best-in-class technologies and the one actually realized by the current configuration of manufacturing and processing systems.
2. Next step entails defining a roadmap for advancements that cope with balancing for each process phase h of the S-W-O-T boxes, the 'System Integration Index' SII_{HL} with the 'Integrability Index of the Phase' IIP_{HL} according to the activity typology (i.e. strategies, tactics, and operations) that are fundamental for the business as well as that verifies the highest gap towards the digitalization and integration of the whole system. The comparison is realized between values for each Hierarchical Level HL computed as in (13) and (14), expressing values through Likert scale.

$$DMI_{HL} = mean(SII_{HL}) * 5 \qquad (13)$$

$$RFA_{HL} = mean(IIP_{HL}) * 5 \qquad (14)$$

Once that this gap is closed, the further typology must be accommodated.

Computations (12) and development roadmap are represented by means of radar charts. An example is provided in Figure 4.14. Red and green arrows highlight priority intervention areas (red areas have the priority).

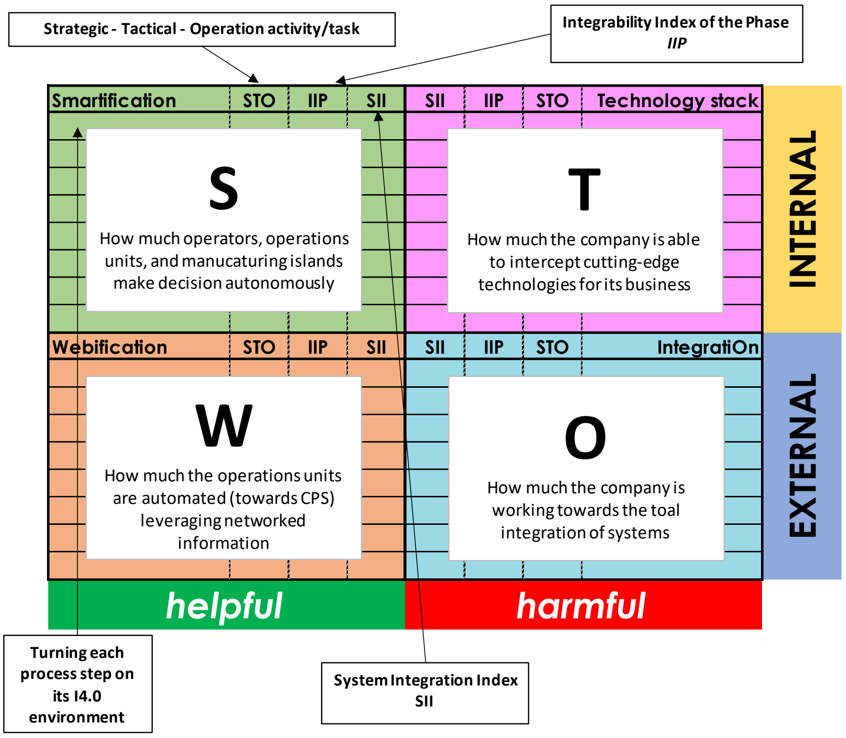
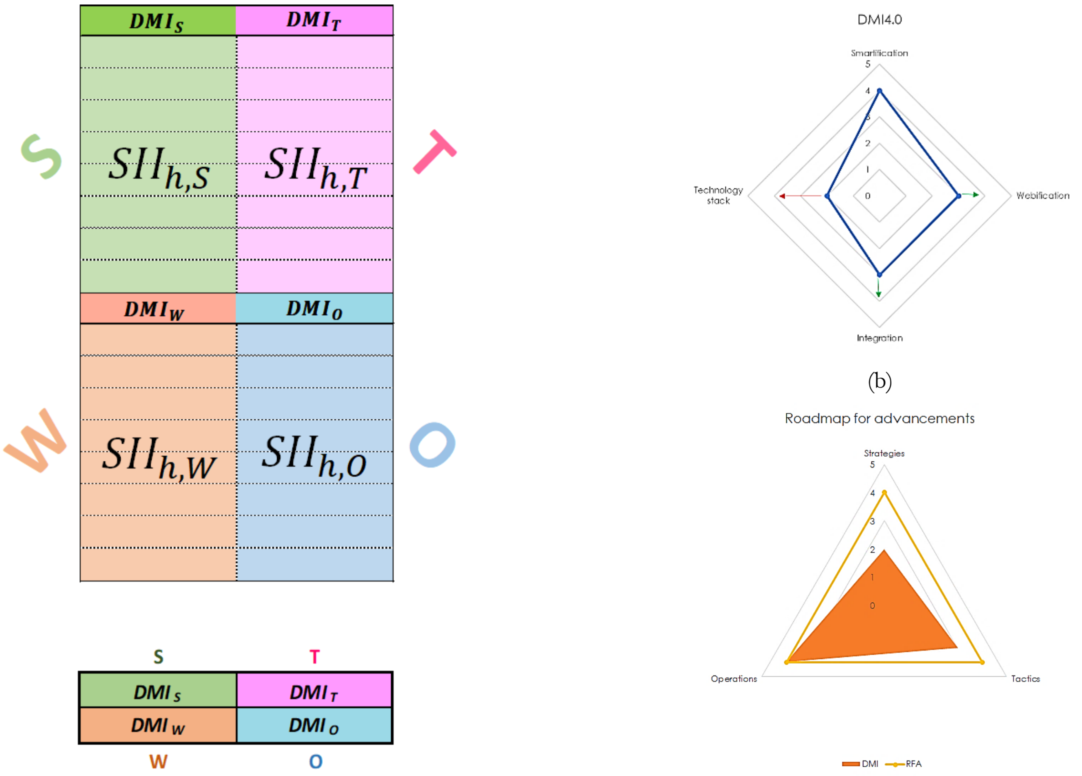


Figure 4.14. The SWOT4i matrix for the SWOT analysis of I4.0

Next subsection provides a case study of the model and two use cases, for better describing the process of stating maturity by using the DMI4.0. The case study and the use case have been developed within the "*Individuazione delle soluzioni tecnologiche abilitanti e modeling delle competenze richieste nella filiera alimentare della provincia di Parma*" funded project.



(a) (b) (c)

Figure 4.15. (a) Computations of DMI in SWOT4i analysis; (b) radar chart for visualizing results; (c) roadmap for advancements

4.4.8 A case study of the DMI4.0: the agro-food industry of the food valley

The pilot case study for validating and verifying the DMI4.0 has involved the cold meat sector players. The process of assessing maturity is rigorously described according to the framework described so far. Artwork and tables relating to this study case and next use case are all provided in the Appendix 4-A.

First step of the framework requires to draw the HoD and make suitable computation. Drawing first three rooms deals with the definition of processes, technologies, and weights of judgement (i.e. Rooms #1 - #3). Tools and methods have been selected on own decision, and choses are arbitrary of the surveyor:

- The process owned by the goods producer (i.e. a manufacturer of 'Prosciutto Crudo' di Parma DOP) has been described directly by the firm himself. The producer remains anonymous in this thesis for confidentiality reasons, and the company is named Pro.PR Spa. The survey has been conducted in the form of unstructured interview. The company has been selected because of two reason:
    i. The firm is a middle-size enterprise, whose manufacturing process and business orientation is characterized by pretty-high level of industrialization and innovative approach compared to other players. The processing plant was rebuilt no more than two years ago after an accident, using cutting-edge technologies of the sector.
    ii. Especially, its will clearly identify directions towards further digitalization of the process and integration of systems for making transparent the SC in which he plays.

  Representation of the process is made by means of flowchart, coded according to Böhm and Jacopini (1966). This step fills in Room #2 of the HoD with process phases. The flowchart of the process is provided in Figure 4.18 in 'neutral form', namely specificities of the process owned by Pro.PR Spa have been not considered.
- Technologies adopted for processing the goods have been described by Pro.PR as it uses them, and by business partners involved in the making of the manufacturing and processing system. Unstructured interviews are used for this purpose. Pro.PR has provided insights to the usefulness of digitalizing each phase of the process. Two systems engineering manufacturers have provided insights to possibility of integrating the process exploiting new technologies and systems, both among phases of the process and among SC nodes (i.e. total integration). This survey fills in Rooms #1, #3 and the digitalization 'anteroom' of the HoD with suitable values.
- The results of the survey so far are here provided 'neutrally', meaning that specific characteristics of process and technologies owned by Pro.PR are neglected for non-disclosure agreement with the partner.
- The correlation of technologies filling in Room #6, is judged together with Pro.PR and systems engineering manufacturers.

As a result of the preparatory survey, the process consists of 11 phases which leverages 11 manufacturing technologies. It is noted that it is just a case that the resulting Room #3 is a squared matrix. Structure of the HoD is provided in Figure 4.19.

- Next, calculations (1) - (11) are computed for filling in rooms#4, #5, #7, and #8 with suitable values.

For a better comprehension of HoD computations and values, all rooms are reported in Table 4.8 (i.e. rooms #1-#5 and #7-#8) and Table 4.9 (i.e. room #6), where data are more readable.

The indexes IIP and SII calculated by the HoD are then inserted and compared in the boxes of the SWOT4i analysis, which constitutes the second step of the DMI4.0 framework for assessing maturity. Results are provided in Table 4.10.

As it emerges from quantitative results, with respect to possible integration of systems, Pro.PR SpA have pushed on integration of all the phases related to operations, for instance (i) maintenance of machineries ($SII = 23\%$, $IIP = 39\%$) and systems ($SII = 22\%$, $IIP = 33\%$), (ii) material handling ($SII = 24\%$, $IIP = 17\%$), and is developing interesting systems for controlling the process phases, namely (i) aging control ($SII = 43\%$, $IIP = 47\%$) and quality control ($SII = 31\%$, $IIP = 53\%$), as well as the (ii) weighting phase which is critical for monitoring the moisture loss of hams ($SII = 34\%$, $IIP = 56\%$). On the contrary, it seems to be currently neglected and emphasis on digital optimization of the salting phase ($SII = 35\%$, $IIP = 73\%$) which is a limitation to all the quality control phase. Finally, the increasing stress on traceability of raw material for high-quality product manufacturing, is highlighted by an increasing digitalization and integration of the system ($SII = 43\%$, $IIP = 67\%$).

This consideration is resumed by the radar-chart expressing the DMI4.0, represented in Figure 4.20. Values are calculated by equation (12). Analyzing the radar-chart is possible to define the first step for a development roadmap: this entails balancing the radar chart, pushing on Smartification. This is because lots of activities involving decision-making processes are still demanded to centralized departments, hence decreasing efficiency and flexibility. Consequently, the system is still not 'Smart'. As it can be seen in room #5 of the HoD, except for weight controls of goods and environmental controls of cold rooms by remote, little intervention can be realized for further digitalize all the technologies allowing a better integration level. For instance, digitally managing the salting phases of the ham has a positive impact on monitoring the aging phase, since operators have data about the 'processing history' and can make decisions on position of hams in the cold room. This is also supposed to need further implementation of IoT infrastructures, positively affecting the 'Webification' and 'Technology stack'. This demonstrates the cyclic nature of the development roadmap fostered by the DMI4.0.

It must be noted that the majority of activities are difficult to be further digitalized, for instance towards automation, although mechatronic technologies support these phases. Moreover, several important phases are difficult to further automate, although related phases can be done. For instance, the quality control is still of olfactory nature and humans sniff at invasive probes for sensing the tasting and deciding upon quality. Although some research is being carried out for switching to visive controls that forecast quality exploiting augmented reality as well as machine learning technologies, systems are still not reliable and marketable by manufacturing technologies. Nonetheless, an owned disruptive system that receive the vocal input from the operator and then handle the ham to the planned cellar position, integrating the information on the company information system, is effective and it actually supports the phase. On the contrary, all the phases related to the quality assurance (e.g. monitoring of environmental conditions of the cold room as well as the ham cellar, e.g. temperature, indoor and outdoor hygrometry and so on) are currently vertical and end-to-end integrated and represent and effective IoT system, however an outlook on horizontal integration is still missed.

A further step towards a development roadmap is realized by the roadmap for advancements, that allows to visualize management practices that have a gap to fill. This gap comes from the comparison between indexes computed for each hierarchical level as in equations (13) and (14). The digitalization level of management organization is well-balanced since the radar-chart is an equilateral triangle. Nonetheless, a gap with potential integration of activities belonging to all management levels exist. It seems to be necessary to primarily speed up the digitalization of strategy activities, since the higher target to achieve again AS-IS level, i.e. Roadmap for advancements (RFA) value 4, and Digital Maturity Index (DMI) value 2. However, since the high similarity of triangles other plans can be devised. For instance, a primary focus can be putted on firm priority, as well as it would be better planning digitalization and integration project of the most childish process phase. For instance, again the salting phase can be significatively improved ($SII = 35\%$, $IIP = 73\%$). Another approach can be working on the most significative process for having a high-level quality end product. Digital improving quality control is possible since a gap between SII and IIP. However, some phases have 'external limitations', namely further integration of phases (i) identification of goods (ID) and (ii) traceability are limited from cultural and technology gap of the upstream SC tiers and some 'grey zone' of regulation of the Consortium.

For validating the DMI4.0 results of the survey has been benchmarked with the narrative description of limits, gaps, and future direction of the cold meat industry. As highlighted by Table 4.6, focal firms of this SC are searching for efficiency of the whole processing line, SC visibility and transparency, as well as business sustainability and respect for the environment. Dealing with this transformation, Pro-PR seems to have a gap in integrating its systems towards decentralization of decision-making processes for intelligent units. Furthermore, Pro-PR is striving to push on SC transparency and traceability, although the whole SC seem to be still not ready for the incoming transformation. Thus, considerations emerged from the unstructured interviews with technology manufacturers are consistent with the result of the survey, and hence the model has been validated.

Use cases of the DMI4.0: the dairy industry and canned vegetable cases

Once the effectiveness and reliability of the model has been proven, the model has been used for two different use cases. The former assesses the maturity of a 'Parmigiano Reggiano' cheese producers for the dairy industry, named her Pa.Re.Cheese Srl for confidentiality reason. In this case, the survey has been carried out involving the producer and two equipment suppliers, namely a machinery manufacturer and systems engineering corporate company. The latter assesses the maturity of the tomato sauce industry chain. Four players have been involved, two goods producers and two systems engineering manufacturer. In both use case the process description filling in room #2 with the process phases has been again described 'neutrally'. In the latter use case, the digitalization weight of technology adopted, i.e. d_{w_i}, is inserted as representing the state-of-the art of producers as emerged from the surveys, rather than as representing the configuration of a single firm. Quantitative results of the use cases are provided in Figure 4.21. Then discussion follows.

Concerning Pa.Re.Cheese Srl, a company operating in the foothills of the Parma district, the most digitalized phases relate to the preparation of ingredient, the management of the recipe, and the controls systems during the preparation of block cheeses preceding the aging phases, and they manly refer to quality assurance and tracking of wheel of cheese arrangement (e,g. cooking $SII = 43\%, IIP = 100\%$; ingredient management $SII = 43\%, IIP = 100\%$; dosing whey and rennet $SII = 43\%, IIP = 100\%$). Traceability is a core element also for aging and warehousing and needs integration for achieving efficiency and visibility. However, phases devoted to the control of goods during the aging process are very craft, (e.g. warehousing $SII = 31\%, IIP = 100\%$). The pushed digitalization of the 'cooking' process is a corrective measure to overcome the lack of control systems that continuously and in near/real-time give information on the aging progress for discriminating quality of end products. Moreover, it needs to be noted that the sample showed that he, and more in general producers as well, strives to 'accept' automation and integration technologies as useful for improving the process towards the value-network creation, and producers seem to be more focused only on their own activities. Although technologies that allows to improve the processes towards automation and operations intelligence (i.e. Smartification mean values $IIP = 75\%$), and total integration (i.e. Integration and Webification, mean values of $IIP = 83\%$ and $IIP = 100\%$) do exist, a gap still exists for the producer in implementing these solutions: for instance the adoption of technologies that can foster digitalization and integration (i.e. Technology stack) verifies a mean value of $SII = 25\%$ whereas the mean possible value of $IIP = 78\%$. All these considerations are simply translated in the radar chart in Figure 4.21, where it is immediate to see that Pa.Re.Cheese is still childish in adopting disruptive technologies of I4.0 and the only web technologies digitalize the process (mainly the phases relating to the cheese wheel preparation). This result is furthermore highlighted by the roadmap for advancements radar-chart. In this chart, the only activities digitalized almost significantly are the operations (i.e. $RFA = 2$), to which belongs the cheese wheels preparation. It seems to lack a focus on value-network creation and market orientation (i.e. $DMI = 1$ for both strategies and tactics), although I4.0 technologies allow to push towards operations (i.e. $RFA = 5$) and tactics (i.e. $RFA = 4$) as well as strategies (i.e. $RFA = 3$).

Since a very different environment, the canned vegetable industry is continuously asking for efficiency and robustness. Two nodes of the SC have been surveyed, i.e. two producers and two manufacturers:

- A big corporate company (still SMEs, however) producing tomato sauce and fruit juice.
- A small company producing tomato sauce.
- Two manufacturers providing systems engineering solutions and equipment for controlling the system. Two aspects arise and concerns are listed below:

Two aspects arise and related concerns are listed below:

1. The product is 'poor' and the plant availability[89] low, thus producers have pushed on automation and mechatronics adoption for (i) maximizing the production volumes, and (ii) continuously monitoring and controlling the system towards (a) process efficiency[90] and (b) decreasing the production unit costs.
2. Continuously monitoring and controlling the system makes way to systems engineering manufacturers to become service providers.

Cross-selling activities for technology manufacturers have been already discussed, and it needs digitalization and integration technology provisioning, that actually they are able to supply. As a result, technology solutions provided by the systems engineering manufactures are installed and used by the goods producers: the digitalization level to achieve (orange blank-chart line in Figure 4.21) is the same of the digitalization level implemented (blue full-colored-chart in Figure 4.21). The only difference relates to the smartification level. Actually, although producers are interesting in disruptive technologies that allows to making best decisions for scheduling activities and maintaining equipment, a gap still exist between (i) what is proposed by technology manufacturers and asked by the firms, and (ii) what is actually bought by the same firms. Of course, developments for tomato sauce producers first entails pushing on smartification and leveraging what engineering manufacturers are able to supply. Next step is about the development of technologies, by systems engineering manufacturer) that can integrate and network SC systems (i.e. $DMI_W = 3$, $DMI_O = 3$, $DMI_T = 2$): technologies are available, but they are not

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[89] Total time in which the plant operates for producing goods in a year: for tomato sauce industry it is limited by the seasonality of raw material

[90] Quantities produced with respect to the plant capability during steady speed operations

implemented toward the value-creation network, and this especially justify the value $DMI_T = 2$, albeit the technology level of solution provided is high-tech. Same consideration can be done concerning the roadmap for advancements: also in this case the operations are very automated and exploit mechatronic technologies, but the total integration point of view towards the value-creation network is missed.

4.4.9 Discussion of results

The DMI4.0 has been designed aiming to make robust data entries: one of the most concern of MMs experienced during the studies for this dissertation is how the 'expert' judge the maturity level of his system. Self-assessment, by compiling a questionnaire has been judged to fuzzy for a reliable assessment of SMEs maturity, since the evaluation depends on what is the knowledge of the 'expert' about I4.0. And a gap still exists between I4.0 and its dissemination within SMEs environment. Thus, it has been designed a framework as robust as possible for avoiding bias. The framework is in three steps. First, the HoD is used for calculating the digitalization level of the company and the integrability of its sub-systems and of the system as a whole: company expert (e.g. the management) describe the company, and technology and I4.0 experts judge the digitalization and integration level AS-IS and possible TO-BE. Second, the SWOT4i maps the level of I4.0 technology adoption: calculations are simple, and they make use of well-proven computations of the HoQ. Finally, it is derived a roadmap for balancing production and management systems adoption of I4.0 technologies and principles. The roadmap is really feasible, and do not ask company that are investigating their digitalization level for the moon. In fact, because of its structure, the DMI4.0 is a MM that can be specifically tailored to the reality that needs to assess its I4.0: it depicts the singularity of the system by describing its processes and characteristics, then it allows to benchmark these with the industry in which the system operates, overcoming benchmarks with realities to much different because the size, and the industry in which they make business. In a nutshell, the DMI4.0 allows a relative comparison of I4.0 potentiality for specific industries, namely criteria of evaluation of how I4.0 can improve the industry all refer to the specific sector in which the analysis is carried on.

For the DMI4.0 design, systems engineering approach has been adopted, namely the business is described by operations processes and technologies adopted. The reason is twofold. Firstly, the reason lies in the manufacturing and process nature of the industry surveyed. Secondly, it has be proven the centrality of technologies for complying with I4.0 principles, namely technology adoption enables digitalizing and networking systems, which eventually leads to the total integration if suitable tuned with the will of change of the company. Furthermore, describing business through technologies allows to 'generalize' the use cases of the DMI4.0. In fact, although the process is mapped individually, computations rules are set regardless the process described, thus the DMI4.0 can be also used for assessing the maturity of systems and subsystems different to the manufacturing one (e.g. surveying the maturity of the business management department as well as logistics one). It is possible to describe any kind of process, since this step is possible to be carried out by means of general-purpose systems engineering modelling tools and techniques, e.g. flowchart. Furthermore, the model can be applied both for mapping the I4.0 maturity of a single system (e.g. a goods producer) as well as its SC (e.g. two nodes, as a goods producer and systems engineering manufacturers). Moreover, since the description of the AS-IS system configuration is realized by mapping it, this overcome some limits of other MMs: for instance, a limit is represented by the fact that 'rules' to judge efficiency, flexibility, sustainability and other characteristics in pure manufacturing industry are very different to those of processing industry. The same applies to environment working in

XTO strategies rather than MTS. In a nutshell, it does not exist a MM designed for fitting in with all business and production strategies. DMI4.0 has been designed towards this direction.

All the characteristics recapped so far, have been proven in practical environments, by means of some use cases of the agro-food industry. In the following some considerations.

The DMI 4.0 have showed its reliability mapping realities very different of the agro-food industry. Results achieved are coherent with those expected but still not proven. This demonstrates the robustness of its design and effectiveness of its main characteristics: the possibility of dynamically assess maturity, namely with a judgement scale relative to the reality surveyed. For instance, since the very craft nature of the dairy process, comparing companies of this industry with automotive industries makes no sense. With DMI4.0, companies of dairy industries are analyzed with respect of the digitalization and integration potentialities of the same industry. An example is worth more descriptions. The radar chart of the dairy and canned vegetable industries Figure 4.21 seems to state that the technology level of the former is higher than the latter. This statement is wrong, of course, since the latter process is high-tech while the former is still very craft. The radar-chart needs to be analyzed case-by case, that is industry-by-industry. The ultimate meaning is that the high-tech level of the canned vegetable industry can allow to further digitalize and integrate systems, and both manufacturers and producers do not still exploit these potentialities.

As a general result of the survey, SMEs of the agro-food industry seems to somehow suffer a kind of 'sense of inferiority', since the very craft nature of some processing tasks, as well as business partnership with financial tough and high-skilled players that are somehow difficult to involve in the improvement of the own system. As a result, they seem to miss the need for digitalizing and integrating their systems, except for some 'illuminated' company.

Finally, the DMI4.0 overcomes some limitations of other MMs, as they are designed for providing "*consultancy services*": the DMI4.0 is transparent, calculation rules are provided and the assessment lies on the process owned by the company interested in assessing its I4.0 maturity: thus, managers can analyze their maturity with or without third parts, remaining steadfast that who assesses the maturity must have knowledge of I4.0 principles and technologies, if not be an expert. The DMI4.0 approach is further cycle-based, namely improvement towards I4.0 systems is seen as a continuously process that update itself each survey, both from the side of what I4.0 is developing into, and where is positioned the company with this regard.

4.5 I4.0 BMs for the agro-food industry

The agro-food use cases of DMI4.0 have given some considerations on how the agro-food industry is evolving and how producers need to adapt themselves to these orientations.

Generally, it can be stated that focusing on two nodes of the SC, namely (i) goods producers and (ii) systems engineering manufacturers, technology proposals are in line with I4.0 evolution, on the other hand producers still strive towards this transformation, mainly for three reasons:

1. Low technology contents of the product
2. The product added value basically recognized by the end customer as traditional product quality
3. A general cultural gap of the agro-food industry

Regardless these limits, I4.0 is an industrial need more than just an opportunity, and some BMs for the agro-food industry nonetheless emerge. In the following section they are discussed briefly.

The increasing needs for flexibility not neglecting efficiency, as well as the interest in services in SCM, manufacturing, logistics, and sales emerged from the survey, are all characteristics that require 'a dynamic allocation of processes and dynamic supply chain structures': SCs need to be no more regarded as rigid physical systems statically arranged towards fixed own specific processes (Ivanov, Tang, Dolgui, Battini, & Das, 2020). This aspect leads to new disruptive manufacturing and SC BMs.

Several definitions of BMs are provided in literature. According to definition of Baden-Fuller and Morgan (2010) BMs are models providing generic level descriptors of how firms organize themselves to create and distribute value in the SC in which they operate, pursuing profits. Different approaches are carried out in scientific literature, and they relate to (i) defining BMs indeed, (ii) defining BM elements and components, (iii) setting a coherent taxonomy that allows to classified BM, and (iv) setting frameworks for either redefining or designing new BMs and making them viable. The focus of this thesis is just on defining possible new elements and components of BMs of the agro-food industry; hence, this thesis sticks to previous study well-established in literature. With these regards, the framework adopted is the one provided by Gassmann, Enkel, and Chesbrough (2010). Principles of new BMs refers to the works of Chesbrough (2007), Chesbrough, Vanhaverbeke, and West (2006), Chesbrough and Appleyard (2007), and Chesbrough (2003).

The framework of Gassmann et al. (2010) has been adopted for providing new BM components for the agro-food industry because its simplicity and clearness that matches the need for 'making easy' the directions and the ultimate meaning of I4.0 r/evolution. It is designed for showing four main drivers of business:

- 'What' is the core component of the business, namely its value proposition
- 'How' the value proposition is created, namely its position within the value chain
- How and what is the 'Value' of the business, namely how revenues are created
- Finally, 'Who' benefits from the business proposition, namely the targeted customer

The framework can be represented as in Figure 4.16 rearranging original graphics of the authors.

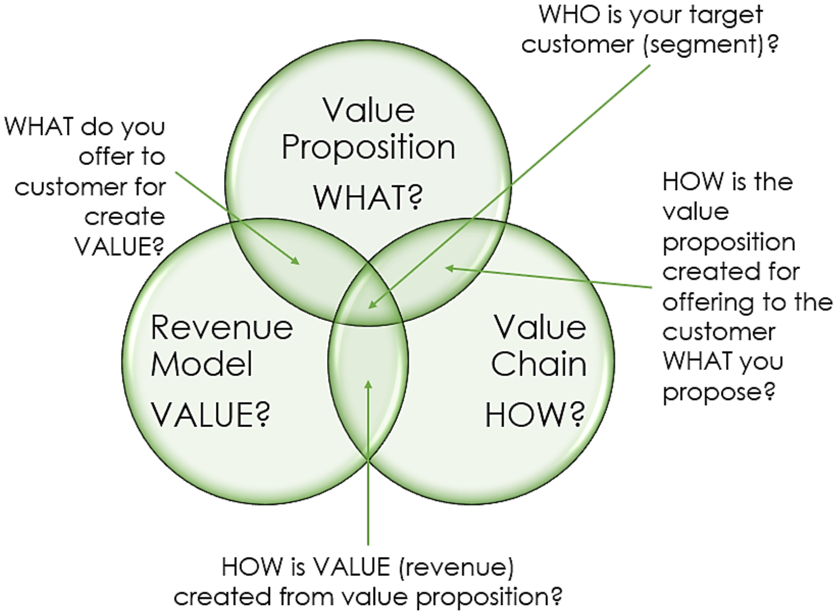

Figure 4.16. BM framework rearranging Gassmann et al. (2010)

Two main principles for new business models raised. The first, of course, refers to the already debated 'Open Innovation', introduced by Chesbrough (2007), Chesbrough, Vanhaverbeke, and West (2006), Chesbrough and Appleyard (2007), and Chesbrough (2003). The principle explains the idea of indifferently outsourcing ad insourcing activities, ideas, assets, and more in general business components. As discussed in Chapter 1 of this thesis, SMEs are still late in openly innovate their business and needs directions. The second principle refers to the work of Zott, Amit, and Massa (2011) and it expands the concept of BMs as systems of interdependent activities that transcend the focal firm and spread throughout the whole SC. It addresses three practices:

1. The exploitations of ICTs in the organizations and among them. The increasing use of ICTs for digitalizing and integrating processes and systems has been demonstrated a requirement for agro-food systems towards their development into I4.0 systems.
2. Laying further stress on value creation, competitive advantage, and firm performance. That is coherent with the need for efficiency and flexibility pursuing by agro-food industry, and also to the service-orientation to which SMEs have to aim and that it is gaining interest in the agro-food SC.
3. Making intelligent managements by using innovative technologies. That sounds as the need for a revolution of the manufacturing systems and more in general, of all business practices that entail dealing with making decisions.

Concepts matches the needs highlighted so far in the analysis of the SMEs especially of the agro-food industry of the food valley.

Different approaches are adopted towards definition of elements for designing new BMs. Biege, Copani, Lay, Marvulli, and Schroeter (2009), Kamp and Parry (2017), and CECIMO[91] have remarked the strategy European companies of moving from a price-based competition to new products design and technology adoption, as well as service-oriented approach of course. Although the interests of developing servitization strategies emerges from both (i) needs of the focal firms onto suppliers' BMs and (ii) needs of end customer onto focal firms' BM (Kamp & Parry, 2017), the servitization as the capacity to design and deliver services and apply payment models on actual and networked performance information and cost intelligence between users and providers (Kamp & Parry, 2017) seems to match just the systems engineering manufacturer and it sounds fuzzy to goods producers. For instance, concerning the focal firms of the agro-food industry, approaches such as selling-services-rather-than-products seems to be translated into selling-the-process-rather-than-the-final-commodity. But as stated by goods producers themselves:

> *An approach towards servitization seem to be rather related to Product Quality practices more than to servitization, although some innovative approach could be conducted aiming at the total 'customization of the finished product' through proprietary process phases directly designed by the end customer.*

For instance, big players of the retail channels not rarely ask for particular processes or process phases, leveraging their purchasing power upon products that fit in with their market demand instead of a traditional price war by leveraging its purchasing capacity.

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[91] Source: CECIMO (2011). CECIMO study on the competitiveness of the European machine tool industry. Brussels: CECIMO. Available at: https://www.cecimo.eu/wp-content/uploads/2013/01/Study_on_Competitiveness_of_the_European_Machine_Tool_Industry_-_December_2011.pdf. Last access: 2020.10.05

If the product-centered servitization towards the end customer seems to disappear, the technology exploitation for total integration disclose some new business opportunities towards upstream business partners. Christopher (2000) have noted twenty years ago the need for collaborating in their VN, maintaining their global competitiveness. This collaboration works as merging companies' boundaries into a unique environment offering not only a superior product but also a superior process (Scheer, 2013). By leveraging competencies of network partners in order to respond to market needs can lead to sustainable advantages (Christopher, 2000). Beyond the 'Product Quality'-as-a-Service, other scenarios arise, and they refer to the increasing availability of 'data' generated and acquired by cutting-edge technologies and devices shared among business partners bidirectionally and thus also from focal firm to its suppliers: it has been discussed, in fact, that optimization of production processes overcome focal firm boundary and it interests the entire network (Christopher, 2000). For instance, analyzing how the focal firm uses technologies, systems engineering manufacturer can develop and market new improved equipment and machineries. It is used the term 'VN' instead of SC since this approach effectively let the SC develop into a VN. Managers and consultants of the Italian SMEs agree on this point. As it emerges from a survey carried out for this thesis during the acceleration days of the 'Italian Digital Challenge', a manifestation held in Brussels from 1st to 3rd October 2019 for promoting European funding mechanisms to the Italian SMEs, Italian SMEs still do not grasp the potentiality of digitalization, but this does not mean that no potentialities exist:

> *The data produced can really modify BMs of enterprises that share them with partners, becoming a real core component of the VN. Supplier of course can benefit of data gathered for informing the focal firms of the state of their systems. Nonetheless, the focal firms can leverage the data provided for being involved in the service provided to other business customer, as well as in the development of business solution, achieving cross-selling opportunities becoming an outsourced 'research and development' department of their own suppliers.*

To this extent, also managers involved to the project "*Individuazione delle soluzioni tecnologiche abilitanti e modeling delle competenze richieste nella filiera alimentare della provincia di Parma*" agree, and they refer:

> *Sometimes for Italian SMEs is hard to make business since high costs to face. Agile business structures that limit overhead costs are critical and outsourcing some high value-added but also high-cost activities is of paramount importance. Focal firms can work as fount of wisdom for the VN, providing their knowledge and expertise in the process for supporting partners in making their business.*

Furthermore, the centrality of gathering data and providing them to other business partners is supposed to reinforce the position of the focal firm within the VN:

> *Sharing business data involves all the partners of the network and not less the focal firms, who can make available the raw material traceability data to strengthen the figure of the consortium of affiliation, or even its position towards the end customer (both in a B2B and B2C context) regardless of the protection consortia that can sometimes be a constraint to the free market.*

According to the framework of Gassmann et al. (2010), a possible BM for the agro-food chain is provided in Figure 4.17. In the BM is stressed that data support the value creation within the supply chain, or VN as discussed for I4.0, and allows to generate more earnings, because of optimization of processes and devising of new forms of revenue. Data can be both exploited from local (e.g. internal servers) or networked sources (e.g. cloud), according to the source generating data, and the functionalities that data fulfil.

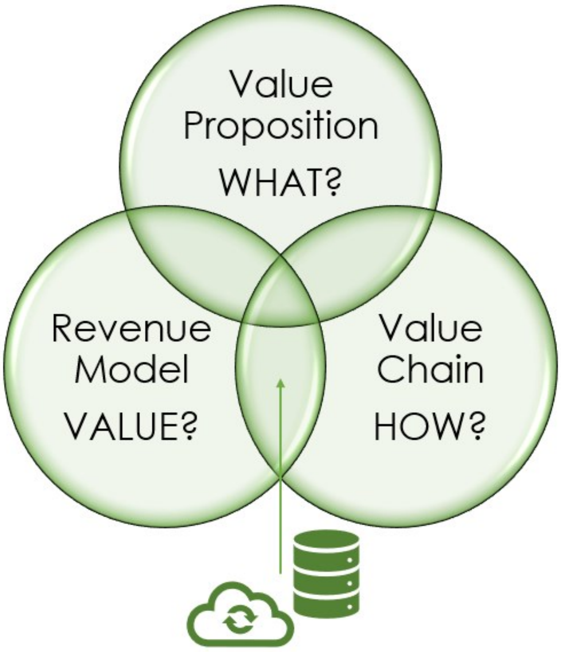

Figure 4.17. A possible new BM for agro-food sector of the food valley

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Appendix 4-A

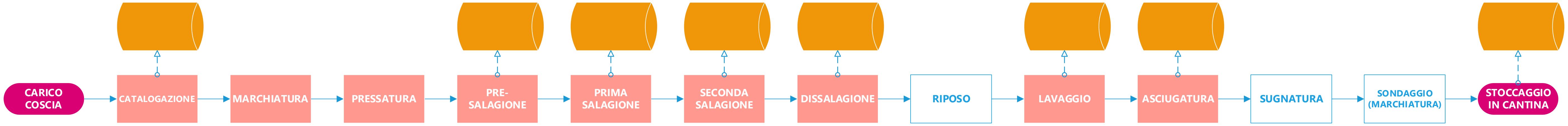


Figure 4.18. A case study of cold meet industry: Pro.PR Spa. For confidentiality reasons, process singularities have been not represented. Process are labeled in Italian language to cope with owner' specificity of task names. Orange servers represents storage of data from the process

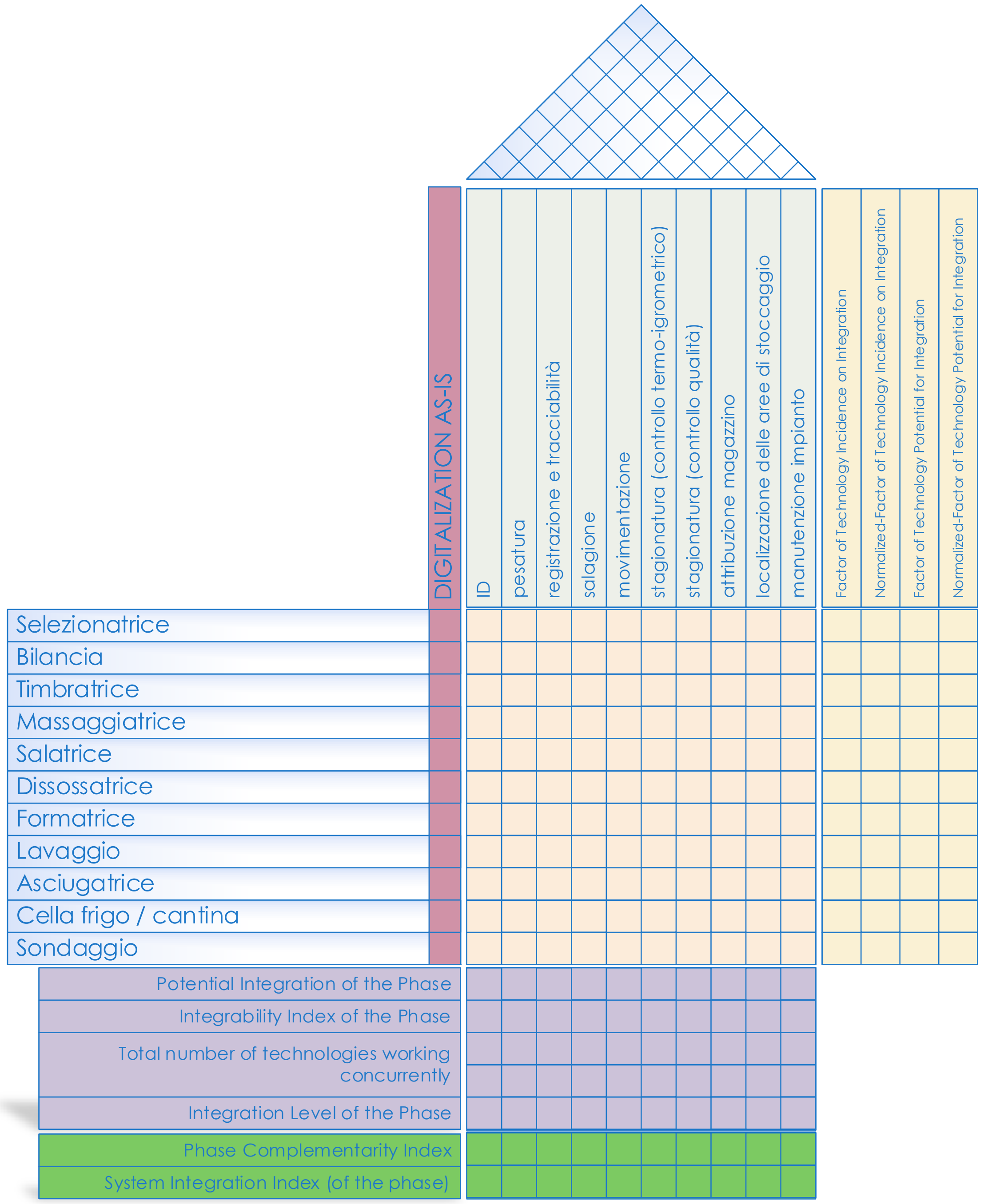
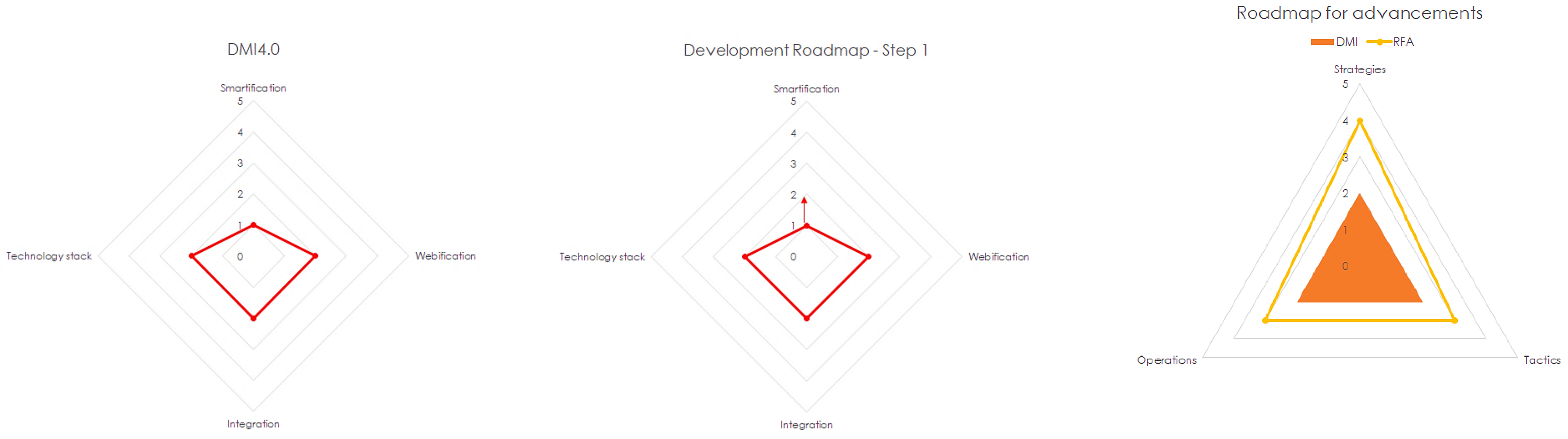
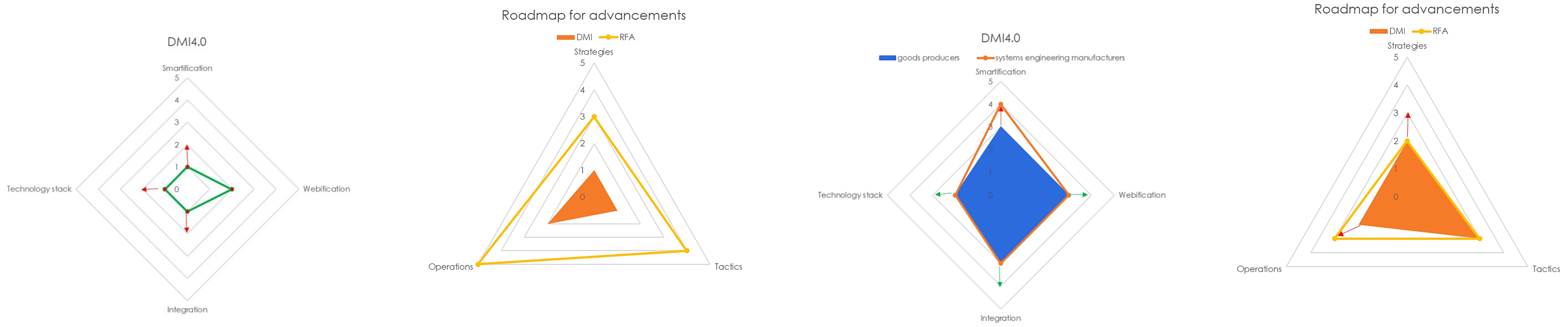


Figure 4.19. HoD structure for Pro.PR Spa of the cold meet industry



(a) (b) (c)

Figure 4.20. DMI4.0: (a) current state, and (b) future state possible to implement; a preliminary step and (c) roadmap for advancements



(a) (b) (c) (d)

Figure 4.21. Use Cases of DMI4.0: (a) and (b): the Pa.Re.Cheese Srl digital maturity and its development roadmap; (c) and (d): the tomato sauce industry SC maturity and its development roadmap

Table 4.8 - HoD for cold meet industry: values from a survey of Pro.PR Spa. Process are labeled in Italian language since the specificity of task names.

		DIGITALIZATION AS-IS ***d_w***	1 ID	2 pesatura	3 registrazione e tracciabilità	4 salagione	5 movimentazione	6 stagionatura (controllo termo-igrometrico)	7 stagionatura (controllo qualità)	8 attribuzione magazzino	9 localizzazione aree di stoccaggio	10 manutenzione macchina	11 manutenzione impianto	Factor of Technology Incidence on Integration ***FTI***	Normalized-Factor of Technology Incidence on Integration ***NFTI***	Factor of Technology Potential for Integration ***FTPI***	Normalized-Factor of Technology Potential for Integration N***FTPI***
			tc_w	***tc_w***	***tc_w***	***tc_w***	***tc_w***	***tc_w***	***tc_w***	***tc_w***	***tc_w***	***tc_w***	***tc_w***				
1	Selezionatrice	3	9	3	9							9	3	99	1%	33	3%
2	Bilancia	9	9	9	9	9		9	9	9	9	9	9	810	8%	90	8%
3	Timbratrice	3	3		3		3					1	1	33	0%	11	1%
4	Massaggiatrice	1		1		3						1	1	6	0%	6	1%
5	Salatrice	3		9		9	1	9	9	9		3	3	156	2%	52	5%
6	Disossatrice	1				3	1		1	1		1	1	8	0%	8	1%
7	Formatrice	1					1			1		1	1	4	0%	4	0%
8	Lavaggio	1				9	1	3	3			1	1	18	0%	18	2%
9	Asciugatrice	3					1	3	3			1	1	27	0%	9	1%
10	Celle frigo / cantina	9	9	3	9			9		9	9	9	9	594	6%	66	6%
11	Sondaggio	3	9		3		3	3	3	9	9	3	3	135	1%	45	4%
	Potential Integration of the Phase	***PIP***	4.33	2.78	3.67	3.67	1.22	4.00	3.11	4.22	3.00	4.33	3.67				
	Integrability Index of the Phase	***IIP***	87%	56%	73%	73%	17%	67%	52%	70%	100%	39%	33%				
	Total number of technologies working concurrently	***T***	5	5	5	5	7	6	6	6	3	11	11				
	Integration Level of the Phase	***ILP***	2.78	1.79	2.56	1.52	0.33	2.59	1.60	2.69	2.33	2.68	2.46				
	Phase Integration Index	***PII***	56%	36%	51%	30%	5%	43%	27%	45%	78%	24%	22%				
	Phase Complementarity Index	***PCI***	44%	32%	41%	40%	42%	43%	35%	46%	70%	22%	22%				
	System Integration Index (of the phase)	***SII***	50%	34%	46%	35%	24%	43%	31%	46%	74%	23%	22%				

Table 4.9 - Matrix for Technology correlation of Pro.PR Spa case study

PROCESS CORRELATION MATRIX	1	2	3	4	5	6	7	8	9	10	11
1	-	1	1	1	0	0	1	1	1	0	0
2	1	-	1	1	1	1	1	0	0	0	0
3	1	1	-	1	0	0	1	1	0	0	0
4	1	1	1	-	0	0	1	1	1	0	0
5	0	1	0	0	-	0	0	1	1	0	0
6	0	1	0	0	0	-	1	1	1	0	1
7	1	1	1	1	0	1	-	1	1	0	1
8	1	0	1	1	1	1	1	-	1	0	1
9	1	0	0	1	1	1	1	1	-	0	1
10	0	0	0	0	0	0	0	0	0	-	1
11	0	0	0	0	0	1	1	1	1	1	-

Table 4.10 - SWOT4i analysis for the case study Pro.PR Spa. Process are labeled in Italian language since the specificity of task names.

Smartification	**STO**	***IIP***	***SII***			***SII***	***IIP***	**STO**	**Technology stack**	**INTERNAL**
stagionatura (controllo termo-igrometrico)	O	67%	43%			34%	56%	O	pesatura	
stagionatura (controllo qualità)	T	52%	31%			35%	73%	O	salagione	
manutenzione macchina	T	39%	23%			46%	73%	S	registrazione e tracciabilità	
manutenzione impianto	T	33%	22%			43%	67%	O	stagionatura (controllo termo-igronometrico)	
		0%	0%			31%	52%	T	stagionatura (controllo qualità)	
		0%	0%			50%	87%	T	ID	
		0%	0%			0%	0%			
		0%	0%			0%	0%			
Number of phases involved	4			**S**	**T**			6	Number of phases involved	
Smartification Level TO-BE	2		*AS-IS*	1	2	*AS-IS*		3	Technology stack Level TO-BE	
Webification Level TO-BE	3		*AS-IS*	2	2	*AS-IS*		4	Integration Level TO-BE	
Number of phases involved	7			**W**	**O**			7	Number of phases involved	
Webification	**STO**	***IIP***	***SII***			***SII***	***IIP***	**STO**	**IntegratiOn**	**EXTERNAL**
ID	T	87%	50%			50%	87%	T	ID	
salagione	O	73%	35%			34%	56%	O	pesatura	
attribuzione magazzino	S	70%	46%			35%	73%	O	salagione	
movimentazione	O	17%	24%			31%	52%	T	stagionatura (controllo qualità)	
localizzazione aree di stoccaggio	T	100%	74%			43%	67%	O	stagionatura (controllo termo-igronometrico)	
manutenzione macchina	T	39%	23%			46%	73%	T	registrazione e tracciabilità	
manutenzione impianto	T	33%	22%			74%	100%	T	localizzazione aree di stoccaggio	
		0%	0%			0%	0%			
helpful						***harmful***				

Appendix 4-B

The paper "Bertolini, M., Esposito, G., Neroni, M., & Romagnoli, G. (2019). Maturity Models in Industrial Internet: a Review. *Procedia Manufacturing*, *39*, 1854-1863" (Bertolini et al., 2019) presents a systematic literature review of maturity model in Industry 4.0.

The paper has been presented at the 25th International Conference on Production Research (ICPR) held in Chicago on 9-15 August 2019, and it is available on the web for full text download at link https://www.sciencedirect.com/science/article/pii/S2351978920303176.

5 Conclusions and possible future works

This thesis has collected all the bibliographic and field research retrieved and developed, respectively, during the three years of doctorate. In fact, the thesis has a dual nature. Firstly, it exploits the bibliographic works produced since the introduction of Industry 4.0. Secondly, field research has been conducted. The goal is to respond to three research questions:

(RQ1) How can reference models or reference architectures be adapted to promote adoption of I4.0 principles and technologies in SMEs?

(RQ2) Does a maturity model exist that simply shine a light on principles and technologies to develop I4.0 systems within SMEs environment?

(RQ3) Is the maturity model, introduced to answer to RQ2, effective and viable?

To cope with this goal, this thesis has firstly identified what technologies, assets, structures, and principles are mandatory to align to the present-state (AS-IS) system to the Industry 4.0 r/evolution, however taking into account what is the baseline of SMEs specific realities. The bibliographic research carried out in this thesis has followed a particular research thread, in which Industry 4.0 is seen as the complex of technologies and business principles that have stimulated the mechanism of transformation of companies towards the Smart Factories, adopting an increasing digitization of processes towards systems integration. This process is possible by adopting three specific technology complexes, namely (i) the Internet of Things, (ii) the Big Data and relative analytics, (iii) the Cyber-Physical Systems. These technology stack entails Information and Communication Technologies, mechatronics, and automation technologies with a dual aim: (i) creating a network of devices that generates data and collects them through telematic infrastructures; and storing, transforming, and processing data collected for further using them for managing systems, namely the complex of devices, product, processes, people. Several general-purpose and specific technologies can be adopted to realize such a system, but a structured analysis has not been developed in this thesis. In fact, it has been considered that technologies to adopt, although general-purpose, depend on the specific environmental context and industrial sector in which the application is implemented. Therefore, in this thesis specific technologies have been only given as examples pointing some technologies that are currently available to realize certain principles. Hence such approach only suggests the technology typology to be considered rather than specific technologies to adopt.

In order to answer to the first research question RQ1, a Reference Model, namely the Reference Model for Industry 4.0 (RMI4.0) has been developed. The aim of RMI4.0 is to promote the development of systems complying with the Industry 4.0, in the context of Italian SMEs and in particular those of the food valley of the Emilia-Romagna region. Hence, RMI4.0 has been designed with the following characteristics:

- It organizes the technology stack, creating a sort of business plan, with which implementing Industry 4.0 technologies step-by-step, with the aim of building the Smart Factory.
- It provides features to enable for changing the way companies do business in the manufacturing and process industry.

Moreover, it entails two characteristics:

- Graphic simplicity and clearness be understood even in a business environment traditionally reluctant to changes, and whose approach to do business hinders to consider complex systems design adoption.
- The possibility to be practically implemented in environments where coordinated and conservative strategies lack. In fact, these strategies mainly refer to adoption of technologies, of a different era and nature, usually selected according to a cost-driven, rather than a benefit driven approach or judging their suitability.

In addition, rigid business schemes of these companies, mean that the change must be introduced gradually, and disseminated in accordance with the business schemes still existing according to cyclical approaches rather than traditional scale-up approaches.

RMI4.0 has been designed to provide a high-level technology stack and functionality description of Smart Factory and Industry 4.0 systems. It is further enriched by function viewpoints expressing how the three complexes of technologies (i.e. Internet of Things, Big Data and Analytics, and Cyber-Physical Systems) operate to achieve the expected results, i.e. (i) the transformation of the production environment in the Smart Factory, and (ii) the alignment of company business principles with the Industry 4.0 view of the value-network creation.

For validating RMI4.0, its interoperability with other Reference Architectures analyzed during the doctorate studies has been tested. RMI4.0 provides a starting point for interested developers to guide SMEs when they want to adopt systems architecture of Industry 4.0 to improve their business position. Two scenarios arise and they relate to the a three-step process of (i) designing a Reference Model, (ii) defining a Reference Architecture from the Reference Model[92], (iii) using the Reference Architecture as a concrete architecture of systems (Lin, Miller, et al., 2017):

- Adopting RMI4.0 during the abstraction of the TO-BE system improving the existing. RMI4.0 can be then used to support the actual introduction of other Reference Architectures and architectures already developed by other studies.
- Developing a new Reference Architecture based on RMI4.0 and then deriving a specific architecture for the system to improve.

The second approach is the one which has been considered for designing the RMI4.0, nonetheless also the first is compliant with RMI4.0 since its interoperability has been analyzed. Both the scenarios can be pursued by academic bodies (i.e. Technology Transfer structures), as well as by practitioners. Collaboration among all these players, and in particular with the last one, is particularly desirable given their ability and capability to create effective system architectures, in collaboration with the talent for technology transfer activities in which the University in general, and specifically the University of Parma, have demonstrated over the years to be really efficient. Moreover, practical applications of Reference Architectures in academia seem to lack, and they only relate to tests for validating Reference Architectures proposed by specific studies. Hence, research can be developed towards the collaboration among players for deriving a best-in-class solution to foster Industry 4.0 views of business in SMEs environment.

The technology stack identified has been then used to answer to the second research question RQ2, namely design a maturity model, i.e. the Digital Maturity Index DMI4.0. Although research has been developed for identifying enabling technologies, reference architectures and models, and maturity models for Industry 4.0, the bibliographic research of this thesis have proved that no study exists that considers

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[92] Source: DIN SPEC 91345:2016-04

these three research fields towards a holistic approach. The present thesis fills this gap: a review of enabling technologies allowed to design a technical reference model, to which the maturity model relate. In particular, the proposed DMI4.0 has been used for surveying the state-of-the-art of food valley companies, towards their transformation into Smart Factories that leverage the Industry 4.0 paradigm derived by the RMI4.0. The~~se~~ company involved in the research are manufacturing SMEs (i) mainly operating with hybrid non-make-to-stock strategies and (ii) belonging to the food processing industry. This sample reflects typical companies in the industry.

DMI4.0, in line with all discussion conducted so far, leverages two key factors:

- The digitalization of processes
- The (total) integration of systems

DMI4.0 has been specifically designed for the food processing industry and it has been tested in a practical environment of the agro-food industry, coping with research question RQ3. Results showed that although there are some enlightened producers who have started a transformation path towards Smart Factories and Industry 4.0 a few years ago, many other SMEs are still torn between the will of evolving and their inability to do so, since lack of knowledge, courage, or financial means. In fact, it has been noted that generally SMEs, and specifically those of the agro-food processing industry, suffer from a sort of ‘inferiority complex’ driven by their three characteristics:

- Company and business size and financial means
- Simplicity of the technological processes
- Cultural lag, compared to the surrounding environment, e.g. upstream and downstream business partners, as well as service industry and academia

Accordingly, Industry 4.0 is seen as a lever to take advantage of tax relief when purchasing new machineries and equipment, as well as systems engineering solutions. On the contrary, the opportunity to modernize business systems outmoded is neglected, rather this aspect has to be grasped otherwise they disappear.

Academic research must in this case work to facilitate a dissemination of technologies and business principles, to make effective the adoption of Industry 4.0 in SMEs, and DMI4.0 can support these paths regardless of the specific industrial sector. In fact, its design makes it adaptable to any industry, as it starts as a 'blank tool' in which the way of doing business of the company is not pre-set, and the only pre-setting concerns calculation logics of computations for achieving the results. And these calculation logics are defined regardless the specific application. For successfully validating this aspect, two use case have been carried out, concerning (i) goods producers and (ii) two-node supply chain section entailing goods producers and mechanical engineering industry. However, for further validating the robustness of the model, the maturity of several and diverse supply chain and industries could be investigated using the DMI 4.0. Consequently, researchers can use the DMI4.0 for future research aimed for measuring the maturity of companies with respect to their transformation into Smart Factory utilizing Industry 4.0, as well as the maturity of the entire supply chain towards its transformation into VN. Concerning future use of the DMI 4.0, this allows anyone to assess the maturity of their systems, and it can be also used by the owner of the processes and technologies, since they have a thorough knowledge of the system. However, an approach towards a partnership with Industry 4.0 experts is preferred for not biasing assessments of the AS-IS system and the TO-BE directions to take towards Industry 4.0.

Finally, although a lot of literature has produced maturity models with various and different characteristics, and not least the DMI4.0, there are no studies that analyze the economic benefits of maturity models when implementing Industry 4.0 systems, namely to what extent it supports companies in their digital transformation ensuring an economic advantage over unstructured transformations distributed over time. Further research is needed to evaluate the economic effects of applying maturity models in this context, also with respect to the costs to map the AS-IS system, and especially to develop the suitable TO-BE solution.

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[i] The query string used in Scopus is "(TITLE-ABS-KEY ("reference architecture")) AND (("Industr* 4.0" OR "Smart Manufacturing" OR "IoT" OR "Internet of Things" OR "IIoT" OR "Industrial Internet of Things" OR "Industrial Internet")) AND (manufacturing OR operations OR "Supply Chain") AND (LIMIT-TO (SUBJAREA , "ENGI"))". Whereas the query string used in Web of Science is "("Reference architecture") - Refined by: TOPIC: ("Industr* 4.0" or "Smart Manufacturing" or "Internet of Things" or "IoT" or "Industrial Internet of Things" or "IIoT" or "Industrial Internet") AND WEB OF SCIENCE CATEGORIES: (ENGINEERING MECHANICAL OR ENGINEERING INDUSTRIAL OR ENGINEERING MANUFACTURING OR ENGINEERING MULTIDISCIPLINARY) AND TOPIC: (Manufacturing OR Production OR Supply Chain)".

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