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A roadmap for the integration of human workers and technology in the next generation manufacturing systems: a socio-technical perspective

Doctoral Dissertation of

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Chiara

List of Abbreviations

AR	Augmented Reality
CPS	Cyber-Physical Systems
ERP	Enterprise Resource Planning
HCI	Human-Computer Interaction
HMI	Human-Machine Interface
HTO	Human-Technology-Organisation
IoT	Internet of Things
IoS	Internet of Services
IT	Information Technology
I4.0	Industry 4.0
KPI	Key Performance Indicator
MTM	Machine to Machine
PSS	Product-Service System
STS	Socio-Technical System
VR	Virtual Reality

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EXECUTIVE SUMMARY

Background

Nowadays, we are in the middle of the so-called Fourth Industrial Revolution (Industry 4.0), based on Cyber-Physical Production Systems (CPPS) that combine communication, IT, data, and physical components, transforming traditional manufacturing systems into smart manufacturing systems (Möller, 2016). The Industry 4.0 initiative has been conceived in order to face the market and social trends that nowadays are driving industrial companies. According to Lasi et al. (2014), manufacturing companies are required to be more and more flexible and agile to respond to customer requirements in an effective way, also fulfilling the needs of individualisation in the demand.

In the last years, many companies have started a digital transformation toward the Industry 4.0 paradigm, which encompasses potentially radical changes involving the whole organization in terms of physical infrastructure, manufacturing operations and technologies, organization, human resources, and process management (Gilchrist, 2016). In this context, companies are keen to understand how this paradigm can impact on professional skills and competences, as well as the effect of the new paradigm on company's organization structure (Erol, Jäger, et al., 2016).

However, the new paradigm of Industry 4.0 has been addressed with a strong techno-centric approach by researchers, but also practitioners, lacking a general perspective on how to guide enterprises in the business transformation toward Industry 4.0. In particular, the impacts of the introduction of Industry 4.0 technologies and paradigms on the human work are under-researched and the new role of the operators in the smart factory environment has not been properly explored yet.

The relevance of humans in the transition to Industry 4.0 requires a clear understanding of how humans can be part of a smart manufacturing system, which are the technology-human interactions and how these systems can be designed considering the human factors.

In particular, based on the literature review and the previously discussed issues, three main gaps have been identified:

1. How human tasks are affected by Industry 4.0 technologies
2. New competences and job profiles for smart manufacturing systems
3. Human integration in smart manufacturing systems

Objective

Given that there is not a widely recognised or commonly accepted opinion about how Industry 4.0 will modify the human work and role, this thesis aims at deeply researching on this topic, investigating the impacts of the introduction of Industry 4.0 technologies on the industrial workforce.

To fulfil the identified gaps and moving from the research hypotheses, three research questions have been defined.

RQ1. How do smart technologies affect the tasks of the operator in the context of Industry 4.0?

The first objective of this thesis is to deeply investigate the impacts of Industry 4.0 technologies on the tasks of the operators, providing a useful tool to assess how technological implementation affects the specific set of tasks of workers in the manufacturing context.

RQ2. What are the competences required by introducing new work attributes that exploit Industry 4.0 technologies?

The second objective of this thesis is to understand how the introduction of new Industry 4.0 technologies affects the organisational structure of companies along with the job profiles, in order to link the technological and organisational variables with the related workers' competences.

RQ3. How does a human-centred perspective affect the integration of Industry 4.0 technologies and humans into next generation production systems?

The third objective of this thesis is to explore what is the changing role of humans in the Industry 4.0 manufacturing processes, in order to depict a conceptual model for integrating humans and technologies in a social perspective.

Methodology

This thesis aims at contributing to both the academic and industrial communities. To do this, a research flow has been conceived, represented in Figure 1. The three research questions are addressed using different research methodologies, which are action research, case studies and conceptual modelling. The research is based on both deductive and inductive reasoning. During the PhD research, the author has been involved in several industrial projects with local manufacturing enterprises. In particular, she spent about two years joining the business activities of Brembo S.p.A, a large Italian manufacturer in the automotive sector, which, since 2014, is undertaking a transformation toward Industry 4.0. The observation and participation to a real manufacturing context enabled the author to better understand the requirements, the issues and the challenges of involving the workforce in such a transformation.

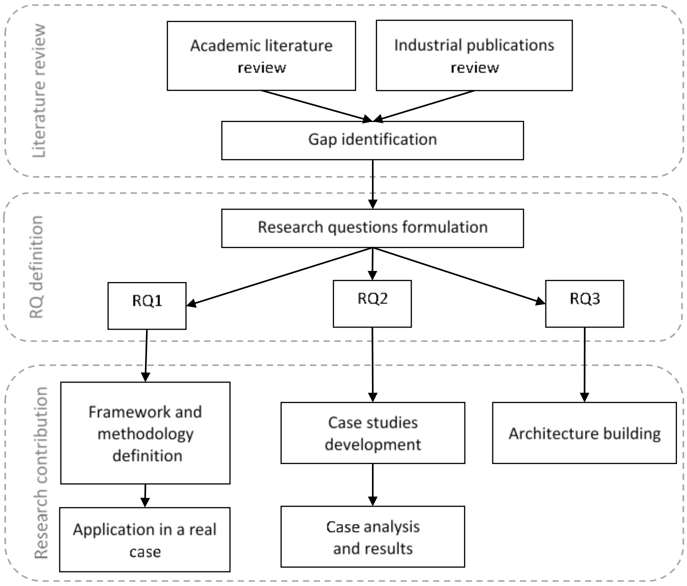

Figure 1 – Research workflow

Research outcome

The answers to the three research questions are discussed hereafter and the main outcomes are finally summarised in Figure 2.

How do smart technologies affect the tasks of the operator in the context of Industry 4.0?

To answer this first research question, a task analysis approach has been developed. A Task Classification Framework has been presented, based on three main relevant classification dimensions, namely routine/non-routine, physical/cognitive, social/individual tasks' features. The aim of the classification is to provide a structured framework in which the tasks' set of specific job profiles could be represented, in order to later assess how the technology does change it. Subsequently, based on this TCF, a methodology to assess the impacts of technology on human tasks has been described in four steps, which are i) the identification of traditional tasks, ii) smart technologies classification, iii) identification of changing tasks, iv) rebalancing of the task-allocation after technology introduction.

The proposed methodology has been applied in an action research project with the company Brembo. In Brembo, the TCF methodology has been applied to the job profile of the production manager having the responsibility of assembly lines. From the comparison of the tasks that were performed before the technology implementation and the new set of tasks after the introduction of two digital tools developed by the company, it emerges that the new tools introduced in the company successfully supported the work of the manager, generally improving and optimising simple and routine activities such as monitoring and data collection, but at the same time creating new opportunities of data analysis, able to improve the overall performance of the department.

Indeed, Industry 4.0 technologies are expected to replace routine and low added value tasks, enlarging the tasks' set concerning the cognitive and non-routine field, which in the long-term can provide companies with an increased knowledge of their production processes and with preventive capabilities, enabling in turns flexibility. However, this poses numerous challenges for companies, among which the qualification and skills of operators, requiring specific attention to training and re-training of the employees in an up-skilling perspective.

What are the competences required by introducing new work attributes that exploit Industry 4.0 technologies?

To answer this research question, two case multiple case studies have been developed aimed at analysing the impacts of the introduction of Industry 4.0 technologies on the job profiles and competences required to workers. The two multiple case studies provide empirical evidence about the existing interconnection between technology implementation and work changes.

Industry 4.0 technologies are affecting the nature of work requiring job profiles characterised by a medium level of vertical and horizontal specialisation. Autonomous Job Profiles are presented as a new typology of job profiles able to support the Industry 4.0 transformation, thanks to the increasing autonomy and the larger number of tasks conferred to workers.

A competence analysis demonstrates how technical competences are of utmost relevance for the companies that are pursuing different training strategies to develop them. Nevertheless, it has been discussed how, in order to achieve a successful technology adoption - that is re-arranging the operational processes of the company to ensure an efficient use of the new technologies introduced - a right combination of technical and soft skills is required.

In addition, it emerges that companies are currently striving their efforts on improving technical skills, lacking in many cases attention to the development of social and soft skills competences. Indeed, many companies are introducing new technical roles to support the implementation of technological innovation and do not care about training people also from a methodological and operational process point of view. In addition, soft skills are underestimated and taken for granted by companies and the result is that they are not developed properly. This suggests that a gap is created between the real competence development undertaken by companies and the suggested well-balanced competence development, which include both technical and soft skills. The asynchronous development of hard (i.e. technical) and soft skills can lead in the long term to poor results in transforming the company processes (both for production activities and service processes) into fully integrated and efficient ones.

Hence, to support an effective transformation toward Industry 4.0, a well-balanced competence development encompassing technical and soft skills is suggested, along with a co-evolution of organisations and technologies.

How does a human-centred perspective affect the integration of Industry 4.0 technologies and humans into next generation production systems?

To answer RQ3, the coexistence of technology and humans in manufacturing systems has been addressed as a socio-technical system, thereby discussing a taxonomy of human roles in smart factories. Keeping the human operator at the centre of the analysis, in order to depict the integration of Industry 4.0 technologies and humans into next generation production system, five scenarios in the evolution of control organisations towards the smart factory paradigm have been identified. This leads to the proposal of a Social Human-in-the-loop Cyber-Physical Production System architecture, which determines that the integration of human operators and technology in a CPPS can be attained through a three-level perspective where a *physical layer* and a *cyber layer* embed human operators that interact with equipment and information systems in a *control layer*. In turn, the control layer makes use of an agent-based perspective to address social interactions and decision-making processes through different types of configurations (from hierarchical to pure heterarchical) of the organization.

As a step further, the impacts of implementing such architecture have been related to the HTO socio-technical model, which has been chosen as a reference for this research work. Finally, a roadmap for the development of a Social HITLCPPS architecture-based manufacturing process has been depicted in 13 steps. The in-depth analysis of human-technology interactions in a CPPS can guide practitioners in defining the most suitable technologies to support the human work, according to their own company strategy.

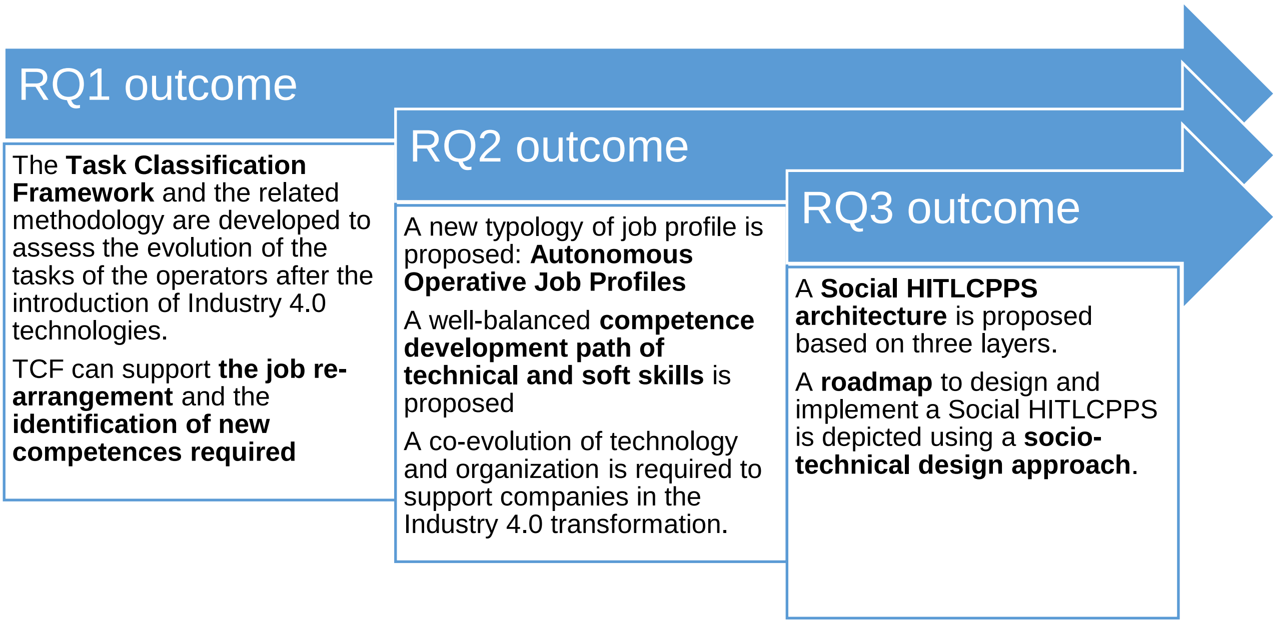

Figure 2 – Research outcomes

Conclusion

The introduction of smart and digital technologies in manufacturing is expected to generate relevant impacts on the workforce, changing the nature of human work and affecting organisational variables. From the review of existing literature about the topic, it emerged that the impacts of Industry 4.0 on the human work and the new role of operators in the smart factories context are under-researched and required further investigation. This thesis aimed at addressing the Industry 4.0 paradigm from a socio-technical perspective, investigating the impacts of the technology introduction on several aspects of the human work, such as the evolution of tasks and the competence and job profiles.

However, some limitations and future research paths can be envisioned.

First, the TCF applicability should be tested in other manufacturing companies, in order to look for similarities in the changing tasks' set of different job profiles and provide a forecasting about how they will evolve.

Also regarding competences and job profiles, a more enlarged case study research will allow a more comprehensive discussion, paving the way to the formalization of the possible roadmaps to be followed by companies and the definition of specific competences required in relation to some relevant companies' features (such as the business, the customers, etc.) and according to different job profiles and levels (such as for managers, operators, etc.).

Finally, an empirical validation of the Social HITLCPPS Architecture is required, in order to test the applicability of such a scenario to a real context. The empirical application will also allow the development of refined mechanisms to regulate the hierarchical/heterarchical structure of decision-making, which are difficult to define at a general level. Starting from the suggested architecture, instructions and rules to design a smart factory environment could be provided in further research.

Published and submitted papers

During the three years' experience of the PhD, the research has been presented at national and international conferences and submitted to international peer-reviewed journals. Hereafter, the list of papers is reported.

Journal Papers

- **Cimini, C.**, Pirola, F., Pinto, R. & Cavalieri, S. (2020). A Human-in-the-loop manufacturing control architecture for the next generation of production systems. *Journal of Manufacturing Systems*. 54, 258–271. https://doi.org/10.1016/j.jmsy.2020.01.002
- **Cimini, C.**, Boffelli, A., Lagorio, A., Kalchschmidt, M. & Pinto, R. (2019). How do Industry 4.0 technologies influence organisational change? An empirical analysis on Italian SMEs. *Journal of Manufacturing Technology Management*. https://doi.org/10.1108/JMTM-04-2019-0135
- Pirola, F., **Cimini, C.** & Pinto, R. (2019) Digital readiness assessment of Italian SMEs: a case-study research. *Journal of Manufacturing Technology Management.* https://doi.org/10.1108/JMTM-09-2018-0305
- **Cimini, C.**, Paschou, T., Adrodegari, F., Rondini, A. & Pezzotta, G. Competence development for the Digital Servitization in industrial firms: a case study research. *Submitted to Journal of Manufacturing Technology Management*.

Conference Papers

- Colli, M., Cavalieri, S., **Cimini, C.**, & Madsen, O. (2020). Digital Transformation Strategies for Achieving Operational Excellence: A Cross-Country Evaluation. *Proceedings of the 53rd Hawaii International Conference on System Sciences*, 4581–4590.
- **Cimini, C.**, Lagorio, A., Pirola, F., & Pinto, R. (2019). Exploring Human Factors in Logistics 4.0: Empirical Evidence from a Case Study. *IFAC-PapersOnLine*, 52(13), 2183-2188.
- Zambetti, M., **Cimini, C.**, Pirola, F. & Pinto, R. (2019). Exploiting data analytics for improved energy management decision-making. *Proceedings of the XXIV Summer School Francesco Turco*, pp.215-221.
- **Cimini, C.**, Pezzotta, G., Pinto, R. & Cavalieri, S. (2019). Industry 4.0 Technologies Impacts in the Manufacturing and Supply Chain Landscape: An Overview, in: Borangiu, T., Trentesaux, D., Thomas, A., Cavalieri, S. (Eds.), *Service Orientation in Holonic and Multi-Agent Manufacturing*. Springer International Publishing, Cham, pp. 109–120.
- **Cimini, C.**, Rondini, A., Pezzotta, G. & Pinto, R. (2018), Smart manufacturing as an enabler of servitization: A framework for the business transformation towards a smart service ecosystem, *Proceedings of the Summer School Francesco Turco*, pp. 341-347.
- Powell, D., Romero, D., Gaiardelli, P., **Cimini, C.**, & Cavalieri, S. (2018). Towards Digital Lean Cyber-Physical Production Systems: Industry 4.0 Technologies as Enablers of Leaner Production. In I. Moon, G. M. Lee, J. Park, D. Kiritsis, & G. von Cieminski (Eds.), *Advances in Production Management Systems. Smart Manufacturing for Industry 4.0*, pp. 353–362, Springer International Publishing
- Piccinini, A., Previdi, F., **Cimini, C.**, Pinto, R., & Pirola, F. (2018). Discrete event simulation for the reconfiguration of a flexible manufacturing plant. *IFAC-PapersOnLine*, 51(11), pp. 465-470.

- **Cimini, C.**, Pinto, R., & Cavalieri, S. (2017). The business transformation towards smart manufacturing: a literature overview about reference models and research agenda. *IFAC-PAPERSONLINE*, *50*, 14952-14957.
- **Cimini, C.**, Pinto, R., Pezzotta, G., & Gaiardelli, P. (2017). The Transition Towards Industry 4.0: Business Opportunities and Expected Impacts for Suppliers and Manufacturers. In *IFIP International Conference on Advances in Production Management Systems* (pp. 119-126). Springer, Cham.
- Jarrahi, F., Pezzotta, G., **Cimini, C.**, & Gaiardelli, P. (2017). Smart service strategies in Industry 4.0: a proposal of a Readiness Assessment Methodology. In *The Spring Servitization Conference 2017 "Internationalisation through Servitization", Lucerne, 15-17 May 2017* (pp. 232-240). Aston University.

Participation to Scientific Conferences and PhD schools

During the PhD programme, international conferences and PhD schools have been attended in order to present the preliminary research outcomes and collect useful comments from other researchers for the development of the research. Hereafter, the list of the attended conferences and PhD schools is reported.

International conferences

- The Industrial Asset Management (IAM) Conference, Brighton, June 15-17 2015. Poster presentation "Real-time self-healing system for a car brake assembly line"
- 8th CIRP IPSS Conference, Bergamo, June 20-21 2016
- 8th IFAC Conference on Modelling, Management and Control, Troyes, 28-30 June 2016
- XXI Summer School "Francesco Turco" - Industrial Systems Engineering, Napoli, 13-15 September 2016
- 3rd IFAC AMEST Workshop on Maintenance Technologies for Performance Enhancement, Biarritz, October 19-21 2016
- 16th IFAC Symposium on Information Control Problems in Manufacturing (INCOM), Bergamo, June 11-13 2018
- 8th Workshop on Service Orientation in Holonic and Multi-Agent Manufacturing (SOHOMA), Bergamo, June 11-12 2018. Paper presentation " Industry 4.0 Technologies Impacts in the Manufacturing and Supply Chain Landscape: An Overview "
- XXIII Summer School "Francesco Turco" – Industrial Systems Engineering, Palermo, September 12-14 2018. Paper presentation " Smart manufacturing as an enabler of servitization: A framework for the business transformation towards a smart service ecosystem"
- XXIV Summer School "Francesco Turco" – Industrial Systems Engineering, Brescia, September 11-13 2019.

PhD schools

- Eden Doctoral Seminar on research methodology in operations management, Bruxelles, February 1-5 2016
- 3rd "PhD on the Go" Workshop, Lecce, May 12-13 2016. PhD Project presentation

- PALM (Product and Asset Lifecycle Management) Doctoral Workshop 2016, Saint-Jean de Luz, October 16-19 2016.   PhD Project presentation.

1. INTRODUCTION

1.1.The context of Industry 4.0 and digitalisation of manufacturing

The modern manufacturing organisations are the consequence of two centuries of continuous improvements of technologies, variations of organisation structures as well as management practices. In the past, three Industrial Revolutions have meaningfully transformed the industrial scenario and the human work in industry (Figure 1.1). First, in 1784, the introduction of the first mechanical weaving loom, supported by the water and steam power, represented the birth of mechanical production facilities. The Second Industrial Revolution, started in the late 19th Century, relied on the application of electrically-powered mass production technologies through the division of labour. In particular, the development of continuous production lines based on both division of labour and the introduction of conveyor belts resulted in a productivity explosion. Finally, the Third Industrial Revolution, which took place in the late part of the 20th Century, was based on the application of electronics and IT, bringing automation in the manufacturing industry (Drath and Horch, 2014).

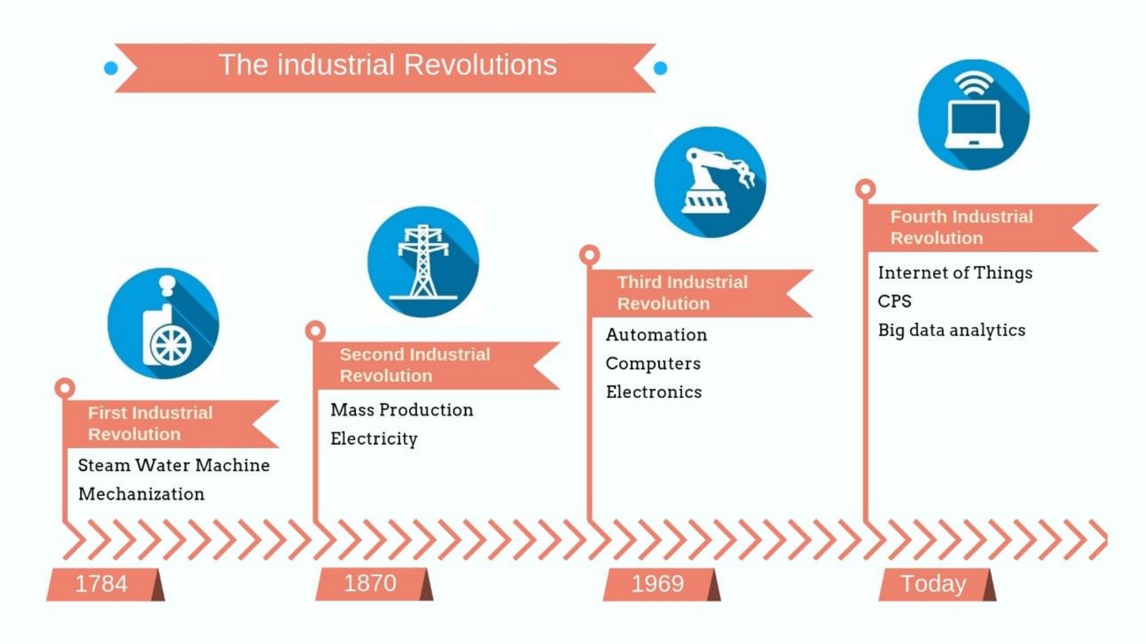

Figure 1.1 – The Four Industrial Revolutions

Nowadays, we are in the middle of the so-called Fourth Industrial Revolution, based on Cyber-Physical Production Systems (CPPS) that combine communication, IT, data, and physical components, transforming traditional manufacturing systems into smart manufacturing systems (Möller, 2016).

The substantial difference of the Fourth Industrial Revolution from the previous ones is that it has not been triggered by the industry on the shopfloor, with the introduction of disruptive technologies such as mechanisation through steam power, mass production, and automation, but it has been predicted a-priori (Drath and Horch, 2014) and established ex-ante (Lasi et al., 2014), generated and promoted by governments and numerous related policies and initiatives (Bauernhansl et al., 2014) to enhance competitiveness through collaborative productivity (Erol, Schumacher, et al., 2016). In fact, the introduction of mechanical and mass production paradigms in the earlier industrial revolutions was a reaction to an increased demand from the market. In contrast, the ongoing Fourth Revolution requires companies to act self-reliant, without a clear demand for increased productivity from the market side (Erol, Schumacher, et al., 2016).

The beginning of the Fourth Industrial Revolution has been formalised in the Hannover Messe, held in 2011 in Germany, where the concept of Industry 4.0 (in German, *Industrie 4.0*) has been presented for the first time as a strategic initiative to promote innovation into the German enterprises, in order to enhance the competitiveness and the German manufacturing industry (Hermann et al., 2015).

In the light of the German *Industrie 4.0*, many related national initiatives have been promoted, such as the *American Manufacturing Partnership*, the French *La Nouvelle France Industriale* (also named *Industrie du Futur*) or the Chinese *Made in China 2025* (Liao et al., 2017), aiming at digitising the manufacturing industry. Also in Italy, in 2016, the strategic policymaking initiative "Piano Nazionale Industria 4.0" has been delivered in order to provide incentives and simplified tax treatments to the enterprises engaged in investments in innovative technologies (Seghezzi and Tiraboschi, 2018).

The German Government presented the concept of Industry 4.0 as a strategic project for the realisation of smart factories, in which interconnected systems are integrated and communicate by the Internet of Things technologies in order to be adaptive and reactive to changes that occur inside or outside the production process (Kang et al., 2016). The core of the Industry 4.0 initiative is the evolution of manufacturing systems towards the adoption of digital technologies. For this reason, other terms, such as smart manufacturing, smart factories, smart production have been used as synonym of Industry 4.0 (Kagermann et al., 2013). In the view of Industry 4.0 proposed by the German Government, the central aspect is the smart factory; however, also smart mobility, smart grids, smart buildings and smart products are considered.

The American National Institute of Standard and Technologies (NIST) better defined the general concept of Smart Manufacturing, which is a "fully-integrated and collaborative manufacturing system that responds in real time to meet the changing demands and conditions in the factory, supply network, and customer needs" (Kang et al., 2016).

The Industry 4.0 initiative has been conceived in order to face the market and social trends that are still driving the industrial companies nowadays. According to Lasi et al. (2014), manufacturing companies are required to be more and more flexible and agile to respond to the customer requirements in an effective way, also fulfilling the needs of individualisation in the demand. To achieve flexibility, faster decision-making procedures are necessary; further, the production systems must be not only adaptive but also self-adjusting and self-optimised (Möller, 2016, p. 20). In addition, environmental issues encourage the manufacturing enterprises to implement sustainable production processes, in order to maximise the resource efficiency and minimise the waste of energy and materials (Davis et al., 2012).

1.2.The impacts of Industry 4.0 on the human work

In the last years, many companies have started a digital transformation journey, which encompasses potentially radical changes involving the whole organization in terms of physical infrastructure, manufacturing operations and technologies, organization, human resources, and process management (Gilchrist, 2016). In this context, companies are keen to understand how the Industry 4.0 paradigm can impact on professional skills and competences, as well as the effect of the new paradigm on company's organization structure (Erol, Jäger, et al., 2016).

However, from 2011, the new paradigm of Industry 4.0 has been addressed with a strong techno-centric approach by researchers, but also practitioners, who paid great attention to the development of key technologies, which enable the transformation of traditional production processes into smart and knowledge-embedded processes, lacking general perspective on how to guide the enterprises in the business transformation toward Industry 4.0. In particular, the impacts of the introduction of Industry 4.0 technologies and paradigms on the human work are under-researched and the new role of the operators in the smart factory environment has not been properly explored yet.

Actually, the strong push to automation and digitalisation brought by Industry 4.0 encouraged researchers to make predictions about the future of jobs. Today's debate mainly focuses to a great extent on the role of technologies in creating or destroying jobs (Weber, 2016; World Economic Forum, 2016). A first scenario provided by Frey and Osborne (2013), based on a study conducted on the USA labour market, suggested that, in the next two decades, the 47% of jobs has to face high risks of automation. However, a more complex perspective, based on a task-based approach and presented in a study of the Organisation for Economic Co-operation and Development (OECD) focussed on the impacts of new technologies on the tasks performed by humans, finally providing a better prediction, envisioning that only 9% of workers could be replaced by automation in the near future (Arntz et al., 2016). At the same time, other researches from big consultancy groups provided opposite scenarios, envisioning a growth in the employment rate, due to the new business opportunities which can be developed by both technology suppliers and end-users (Roland Berger, 2016; Rüßmann et al., 2015).

A survey conducted by Deloitte Consultancy Group better puts the focus on highlighting that technology could have different impacts on occupation, in relation to the nature of human work, suggesting that routine and manual occupations are most likely to be replaced by technology, while non routine and cognitive occupations will increase significantly in next years (Figure 1.2).

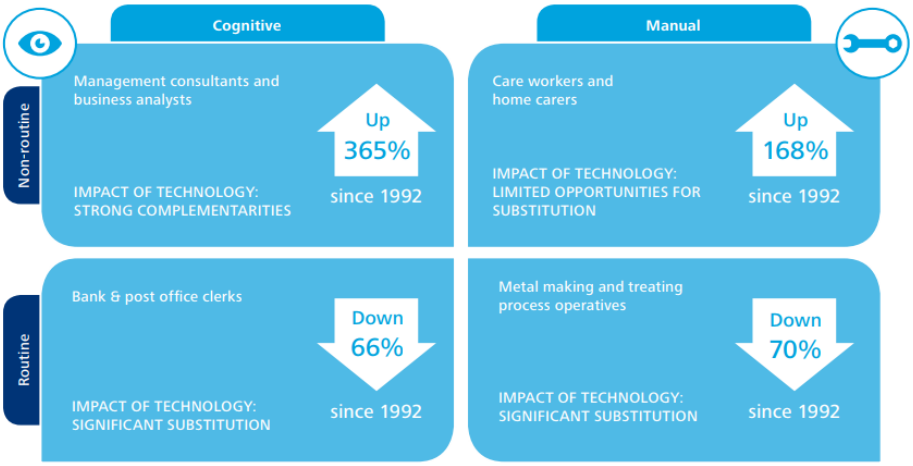

Figure 1.2 – Examples of the effects of technology on employment by nature of occupation (Deloitte, 2015)

A more recent survey conducted by the World Economic Forum pointed out that in few years the ratio of human-machine working hours for different types of tasks will change, as depicted in Figure 1.3, suggesting that, despite machines will increase their presence disadvantaging the human work, emerging tasks and role will emerge (World Manufacturing Forum, 2019).

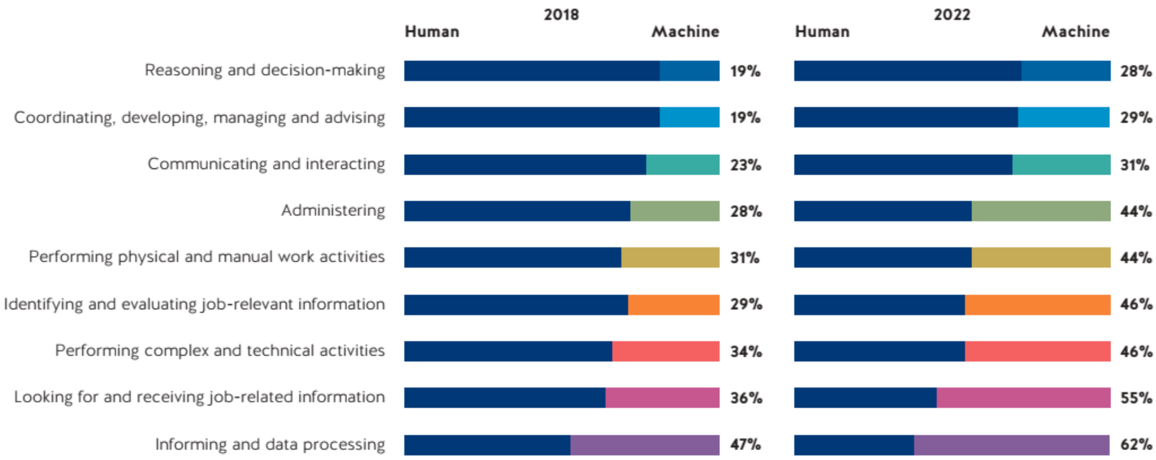

Figure 1.3 – Ratio of human-machine working hours, 2018 vs 2022 (World Manufacturing Forum, 2019)

What is quite widely recognised is that in some cases automation will significantly reduce the presence of the workforce; in other cases, however, technology will increase the level of complexity of production systems, not affecting the overall number of jobs, but rather contributing to the creation of new professional figures, thus expanding the work offering for the new generations. In this sense, technology can be considered as a complementary element to man - more than a substitute - in the execution of complex and high-value processes.

Accordingly, the data collected and shown by the European Commission in the Digital Transformation Scorecard 2018 demonstrate how only the 7% of the interviewed companies will decrease the number of employees, while in the most of the cases it will remain stable or even increase (Figure 1.4).

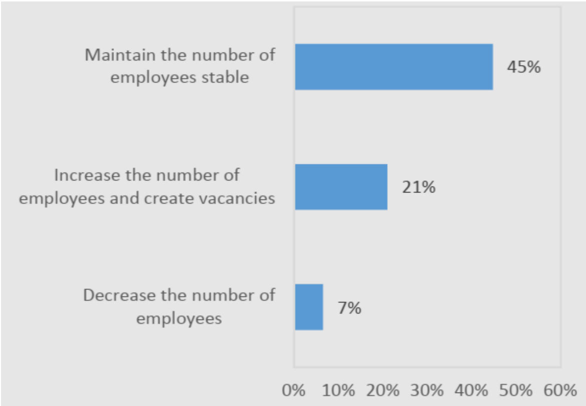

Figure 1.4 – Impacts of digital technology adoption on the employees' number (European Commission, 2018)

Another interesting perspective is provided by Roland Berger (2016), which suggests that in the first years of new technologies' adoption the number of employees will decrease, but then new business models and reinvestments in new industrial equipment or activities will have a positive effect on the workforce number in the long term (Figure 1.5).

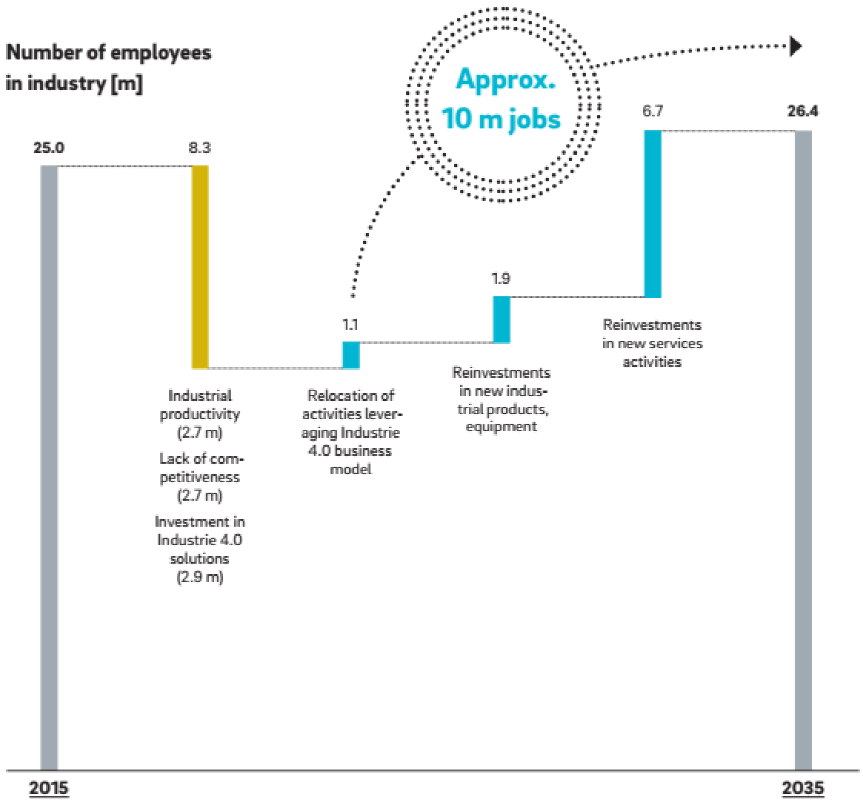

Figure 1.5 – Long-term impacts of technology on employee number (Roland Berger, 2016)

Beyond those more or less accurate predictions about future job losses and human replacement in favour of technology, researchers and practitioners are managing to figure out how Industry 4.0 will reshape the role of humans in the manufacturing landscape.

Several research streams emerge. The need for quantifying and deeply investigate if new technological advances will modify or replace human work in manufacturing is of utmost importance. Along with this, the new competences and skillsets required to the human workforce to be efficient in Industry 4.0 need to be identified. Also, the most appropriate organisation strategies and new operational mechanisms involving humans in the new concept of smart factories require more investigation.

The motivation beyond the need for deeply investigating the human factors in the Industry 4.0 context is twofold. First, according to the last updates of the statistics provided by the International Labour Organisation ("ILOSTAT database", 2019), the industrial sector employs about the 23% of the total number of workers all over the world. Therefore, the changing conditions in the industrial work may have a great impact on the society as well. Second, historically, issues related to the human factors, such as the workers' involvement, capabilities and mindsets, have been recognised as very relevant variables that strongly affect the successful implementation of technological advancement (Chung, 1996). In relation to Industry 4.0, in particular, it emerges that in the most of the cases, employees are not properly prepared to face the challenges of Industry 4.0 implementation (as an example, see Figure 1.6).

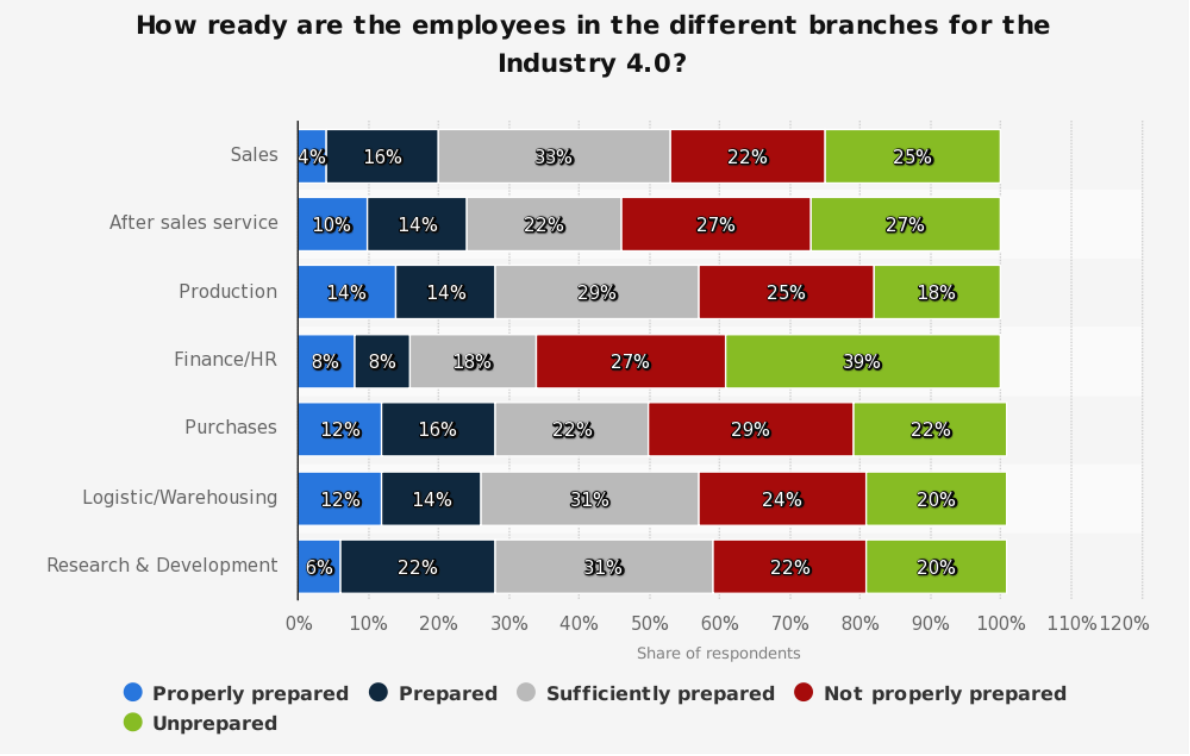

Figure 1.6 – Employee preparation to Industry 4.0 (Staufen, 2015)

Indeed, one of the most relevant issues that companies are facing in their digital transformation journey concerns the huge challenge in employing people with the proper skills to manage the introduction of new technologies. Skilled jobs are becoming increasingly difficult to fill and the talent shortage in 2018 globally reached the 45% (World Manufacturing Forum, 2019).

For these reasons, alongside the development of new technologies, proper investigations and developments in the human-related aspects must be carried out, both at theoretical level, highlighting, for instance, the interdependences between technological implementation and the human capabilities, and at a practical level, to provide manufacturing companies with effective tools to drive their workforce toward the new paradigm of Industry 4.0, that is aligning the technological innovations with a human-centred perspective of the smart factory.

1.3.Thesis objectives and scope

Given that there is not a widely recognised or commonly accepted opinion about how Industry 4.0 will modify the human work and role, this thesis aims at deeply researching on this topic, investigating the impacts of the introduction of Industry 4.0 technologies on the industrial workforce.

In particular, the objective of this thesis is to explore three main topics:

1. <u>The impacts of I4.0 technologies on the human work activities</u>

   It is widely agreed that introducing new technologies in manufacturing will modify the way humans carry out their daily work activities, namely their tasks. Indeed, in the last years, advances in automation, digitalisation and robotics have ushered a new age in which machines can substitute and/or complement people in an increasingly wider range of work activities. Among the plethora of technologies which are mentioned under the umbrella of Industry 4.0, different impacts can be observed, in relation to the different technological capabilities. Moreover, the concept of Operator 4.0, recently emerged in literature, suggests that the human capabilities can be augmented and assisted by technologies in the smart factory in several ways, opening different directions for the replacement of some tasks and the development of new tasks as well.

   For this reason, the *first objective of this thesis is to deeply investigate the impacts of Industry 4.0 technologies on the tasks of the operators, providing a useful tool to assess how technological implementation affects the specific set of tasks of workers in the manufacturing context.*

2. <u>The evolution of competences and job roles in relation to the I4.0 technology adoption</u>

In the new paradigm of Industry 4.0, the key issue of how new technologies will reshape the nature of human work also includes the evolution of job profiles and competences required to the workforce to be efficient in the new industrial landscape. Actually, the skills of the existing workforce may be, on average, not ready to cope with the challenges of automation and digitalisation, and specific investigation is needed to understand how to upgrade workers' competences, both in terms of technical abilities required as well as in terms of new soft skills. Competences and skills are related to the evolution of the job profiles and their features (such as polyvalence and specialisation) and, at the same time, to the changing organisational models that companies need to adopt to be more flexible in the Industry 4.0 context.

The second objective of this thesis, therefore, is to understand how the introduction of new Industry 4.0 technologies affects the organisational structure of companies along with the job profiles, in order to link the technological and organisational variables with the related workers' competences.

3. <u>The integration of human and I4.0 technology capabilities to manage the smart factory environment</u>

The evolution of manufacturing processes towards Industry 4.0 will finally reshape the role of humans in the factories. New operating models will require proper integration of human and technological capabilities. The management and decision-making processes, in fact, will become increasingly shared between humans and machines, requiring new models to govern the management and control of the manufacturing processes. The operators in the factory of the future will be immersed in an "intelligent" environment, with the possibility to share and receive real-time information from many smart objects (such as machine, robots, product, etc.) and they will be involved in new collaboration mechanisms and social interactions, which will highly affect the performance of the whole smart manufacturing system. For this reason, rethinking manufacturing systems from a human-centred perspective will make it possible to use digital technologies to enhance the unique and irreplaceable capabilities of man, who will continue to play a fundamental role in the factories of the future.

The third objective of this thesis, then, is to explore what is the changing role of humans in the Industry 4.0 manufacturing processes, in order to depict a conceptual model for integrating humans and technologies in a social perspective.

Fulfilling the above-explained research needs require a large investigation both at theoretical and practical level. For this reason, in order to provide a useful contribution to both academia and practice, during the three years of the PhD programme, the author has been involved in several projects in collaboration with local manufacturing companies. In particular, the author spent about two years joining and allowed to test the applicability of some methods which have been developed during the PhD research, actively contributing to achieving the previously defined objectives. In particular, the action research project in collaboration with Brembo will be discussed in Section 4.4, while the results of two multiple case studies conducted in about 20 manufacturing companies will be the focus of Section 5.

1.4. Thesis structure

To guide the reader throughout this PhD research, hereafter the structure of the thesis is explained and depicted in Figure 1.7.

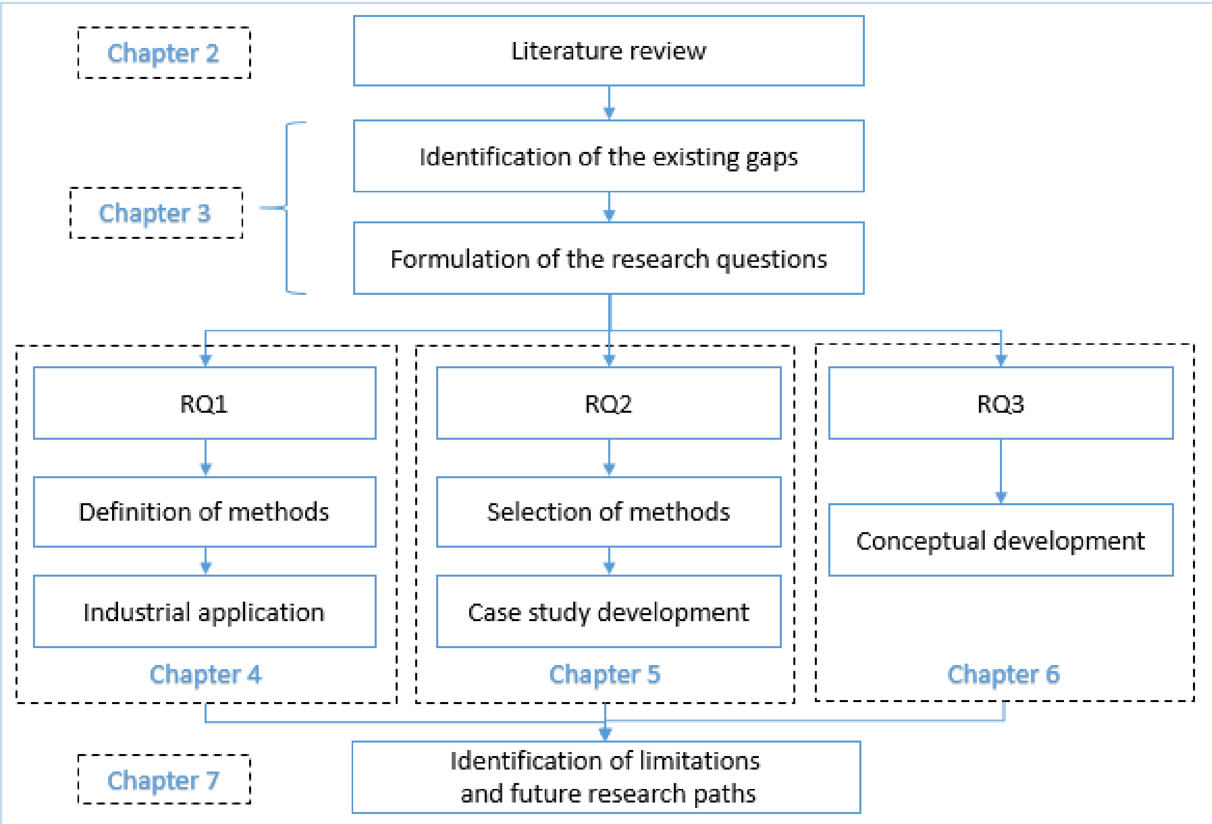

Figure 1.7 – Thesis structure

In Chapter 2, the background of this research is presented. It includes a wide perspective on the Industry 4.0-related concepts, starting from the enabling technologies, to the business transformation and Industry 4.0 reference models proposed in the literature. When the author started the PhD research, Industry 4.0 concept was a quite novel research topic yet. For this reason and due to the lack of journal contributions about the topic, as a preliminary step of the research, a large amount of academic and non-academic literature has been scanned and reviewed. Along with journal and conference papers, documents from consultancy groups and industry have been considered, such as the reports provided by the German *Plattform Industrie 4.0* that first started to research on the topic.

Chapter 3 aims at pointing out the objectives of the thesis. In doing so, a critical discussion about the literature gaps that emerged from the previous literature analysis is provided. The objectives of the thesis are then defined and a research workflow is depicted. In order to fulfil these objectives and answer the research questions, several research methodologies are identified and discussed.

Chapter 4, 5, and 6 represent the core contribution of this work, since they encompass the specific research investigations and results related to the three research questions. In particular:

- Chapter 4 aims at identifying how Industry 4.0 technologies affect the human work in terms of tasks. After the presentation of a Task Classification Framework and its related methodology, an industrial application is developed.
- Chapter 5 includes the discussion about new competences and job profiles for Industry 4.0, providing a competence development path, supported by two different multiple-case study researches.
- Chapter 6, finally, aims at depicting a more general scenario of integration of human and technology capabilities in the Industry 4.0 context, namely in a smart factory. The core contribution of the chapter is a conceptual framework (the Social Human-In-The-Loop Cyber-Physical Production Systems architecture) that provide a proposal for the development of a smart manufacturing system in which humans and technology cooperate and are socially integrated.

Chapter 7 concludes the thesis, summarising the main contributions and results. Limitations are then identified, in order to propose further developments of the research.

2. BACKGROUND

This chapter aims at providing an overview of the new manufacturing paradigm which has been referred to as Industry 4.0 in last years.

Starting from the evolution of manufacturing systems over the last twenty years, the definitions and the main features of Industry 4.0 are discussed, based on the available scientific literature. In particular, the enabling technologies of Industry 4.0 are listed and described, and the new concept of smart factories is depicted.

In the light of these theoretical concepts that are the basis of the Industry 4.0, its impacts on the manufacturing companies is discussed afterwards. In particular, the impacts of technologies are expected to involve many business areas, such as the production, the supply chain, the engineering, etc.

Strictly connected to this, in this chapter, a discussion about the business transformation towards Industry 4.0 is presented. Indeed, in the light of these new technological trends, manufacturing companies are expected to change their business and operating models, to fully exploit the potentials of technologies, facing, at the same time, several challenges. In order to support companies to develop smart manufacturing systems, some reference models have been proposed in literature.

However, from their analysis, it emerges that one of the most neglected topics is the human involvement. For this reason, a reference model for Industry 4.0 including the human aspects has been searched. The socio-technical systems theory has been identified as useful to address the transformation towards Industry 4.0 considering both human and technological aspects. More specifically, the Human-Technology-Organisation model has been evaluated as suitable for researching in this topic. In the final part of the chapter, therefore, the HTO model is discussed.

This chapter offers the background to develop the whole research, identifying the premises which led in the last years to the concept of Industry 4.0 and providing the foundation to deeply explore this paradigm in order to evaluate its impacts on the human work, which represents the core topic of this thesis. In particular, the HTO socio-technical model will be used in the next chapters to identify the most relevant literature gaps and set the objectives of the research.

2.1.Industry 4.0 foundations

In recent years, many manufacturing companies have been involved in changing their production processes to face the market drivers of high-quality standards and agility required by the customers, while still maintaining low costs for the products (Koren and Shpitalni, 2010). In this scenario, the growth of IT technologies supporting the manufacturing processes paved the way to the Fourth Industrial Revolution, namely Industry 4.0.

To better understand the background behind the first concepts of Industry 4.0 and CPPS, an introduction of the main technological trends that have driven the research about manufacturing systems in the last years is required. In particular, Monostori (2014) identifies some roots of CPPS in manufacturing, such as Reconfigurable Manufacturing Systems, Intelligent Manufacturing Systems, Digital Factory, Biological Manufacturing Systems, Holonic and Multi-Agent Manufacturing Systems.

Actually, since the last years of the 1990s, the concept of flexible and adaptive factories has been researched, because of the increasing need for agility and responsive adaptation to the customer requirements, under the label of Intelligent Manufacturing Systems (Colombo et al., 2006). In particular, the new paradigm of Reconfigurable Manufacturing Systems was developed. As defined by Koren et al. (1999), *"a Reconfigurable Manufacturing System (RMS) is designed at the outset for rapid change in structure, as well as in hardware and software components, in order to quickly adjust production capacity and functionality within a part family in response to sudden changes in market or in regulatory requirements"*. As discussed also by ElMaraghy (2005), the objective of RMS is "*to provide exactly the functionality and the capacity that is needed, when is needed*" also through the introduction of new enabling technologies during the production system lifecycle. Koren and Shpitalni (2010) defined a Reconfigurable Manufacturing System using five distinctive characteristics: i) Modularity: the production system is made of modular components; ii) Integrability: all the modules are designed in order to be easily integrated and respond to customer requirements; iii) Convertibility: the production system allows a substantial reduction of setup time to change the type of product; iv) Customisation: the system is built around a family of parts that will be manufactured on the machines. The customisation also regards the control of the system; v) Diagnosability: the production system is highly interconnected to gather operation and maintenance data supporting the definition of operative and maintenance strategies.

In this context, many other researches about advanced automation solutions for manufacturing have been published, also introducing the concept of intelligence embedded in the production system (Carpanzano and Jovane, 2007; ElMaraghy, 2008; Molina et al., 2005). The concept of Evolvable Production Systems was further developed, focusing on the predicted and unpredicted changes that can occur during the production, to support the design of manufacturing systems characterised by high modularity and adaptability (Maffei et al., 2010). Thereafter, the first attempts of defining the smart factory appear in literature since 2010. Zuehlke (2010) discusses about a "factory-of-things" describing the SmartFactory^{KL} initiative, a demonstration and research testbed for academic and industrial partner, in which every object is networked with IoT technologies and is embedded with intelligence.

In SmartFactory[KL], a production line for the production of coloured liquid soap has been implemented with a modular structure of smart devices, in which each component acts as sensor/actuator, by the use of radio technologies (e.g. Bluetooth, RFID, NFC). The communication is wireless, and each device is equipped with a micro-controller, that makes it aware of its function and position inside the production process enabling self-decision to achieve a high flexible configuration and re-configuration of the line.

Yoon et al., in 2012, introduces the concept of Ubiquitous Factory as a synonym of smart factory, with the focus on the potential of ubiquitous computing technologies applied to manufacturing. The framework suggested by Yoon et al. (2012) is founded on three main requirements of a production system: i) transparency, which means pervasive data acquisition and reliable data exchange inside the factory; ii) autonomy, which refers to self-adaptability through control systems and self-diagnosis, and iii) sustainability, which suggests a real-time energy management in order to achieve the maximum resource efficiency. Based on these principles, the authors depicted a reference architecture composed of four levels, from the shop floor layer to the lifecycle layer, via the application system layer and the information infrastructure layer.

Smart factories and ubiquitous factory concepts, however, should be considered only as precursors of the Industry 4.0 as we know it today. Indeed, the three main features of the Industry 4.0 concept are reported in the final report of the *German Plattform Industrie 4.0*, published in April 2013 as a set of recommendations for the smart manufacturing implementation in the German context (Kagermann et al., 2013). It is worth noting that, in the above-mentioned report, the Industry 4.0 description is contained in a wider vision, in which the smart factory is only one of the parts of a completely connected world that includes smart mobility and logistics, smart grids, smart building and smart products. In such a complex system, the Internet of Things (IoT) and Internet of Services (IoS) enable the communication and the sharing of information outside the smart factory, while inside the key technology that transforms the production process into smart processes is based on Cyber-Physical System (CPS).

According to Kagermann, Wahlster, et al. (2013), the Industry 4.0 model is based on three key features:

1. *Horizontal integration through value networks* refers to the connection of different production systems in an intelligent supply chain, which enable the communication and the strategic synchronisation of suppliers and customers outside the factory, but also the integration of the internal value chain from engineering to sales (Figure 2.1);

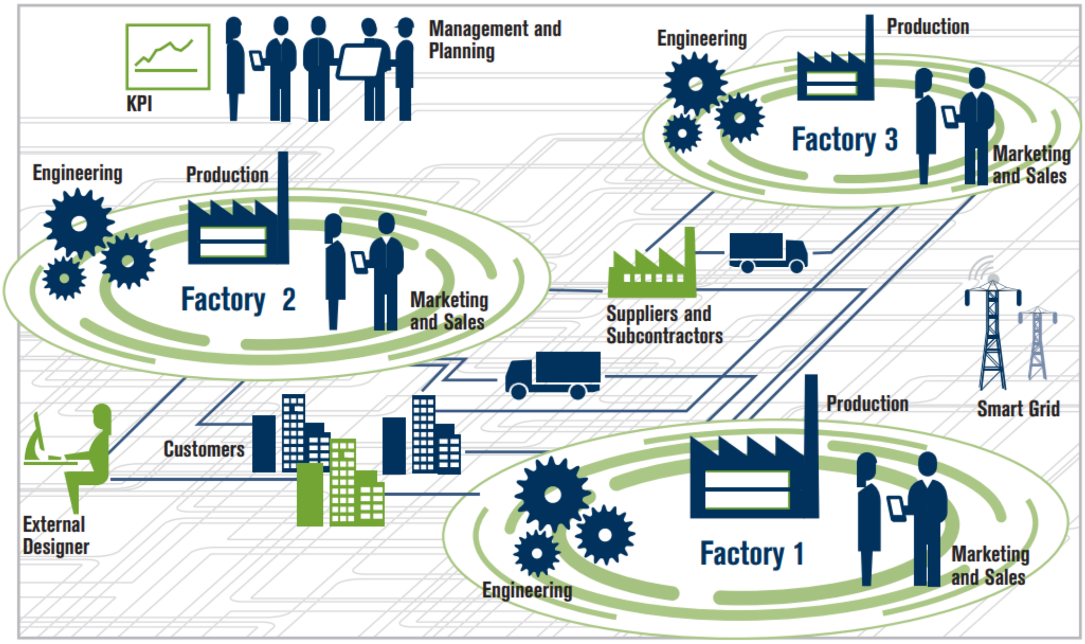

Figure 2.1 – Horizontal integration through value networks
(Kagermann, Wahlster, et al., 2013)

2. *Vertical integration and networked manufacturing systems* is related to the Information Technology (IT) infrastructure of the production systems and suggests a network in which the information can flow from the automation and control systems to the enterprise ERP, also enabling feedback and corrective actions (Figure 2.2).

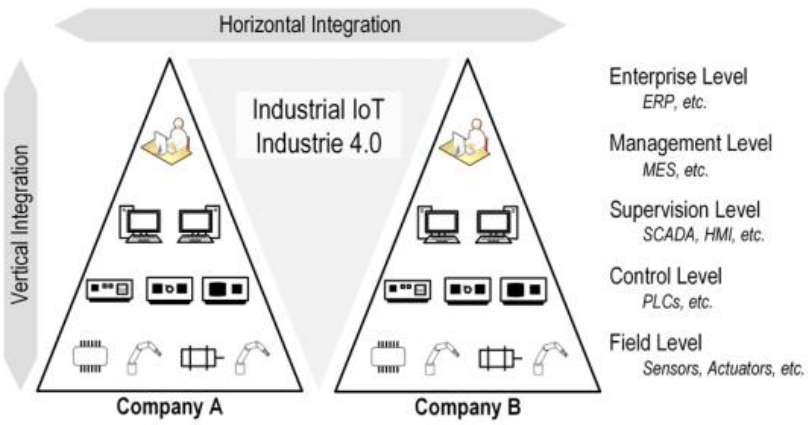

Figure 2.2 – Vertical integration inside the enterprise and horizontal integration between enterprises
(Lesjak et al., 2016)

3. *End-to-end digital integration of engineering across the entire value chain* provides a model for the value creation process, in which digitalisation enables the communication through the various stages of the engineering of products and services, from the products/process development to the maintenance and recycle (Figure 2.3).

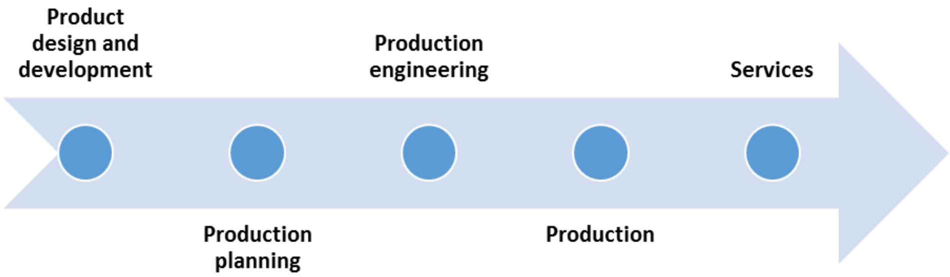

Figure 2.3 – End-to-end digital integration of engineering across the entire value chain (Adapted from Kagermann, Wahlster, et al., 2013)

The Industry 4.0 initiative exploited all the results of previous researches by converging all the emerging trends in the automation to a more general framework. In this sense, the report published by the *Plattform Industrie 4.0* (Kagermann et al., 2013) represents a crucial point, where the previous researches were summarised and gave birth to a new global perspective on smart manufacturing. In fact, the three levels of integration depicted by Kagermann properly summarised all the characteristics suggested for Reconfigurable Manufacturing System and enlarged the framework with the introduction of new emerging technologies.

2.2.Industry 4.0 definitions

From 2011, many definitions of Industry 4.0 have been provided both from academia and industrial associations, aiming at identifying the conceptual characteristics of such a revolution. Despite several attempts, it is possible to recognise that the term Industry 4.0 is not yet ultimately defined. The German telecommunications association BITKOM reveals more than 100 different definitions of Industry 4.0 (Bidet-Mayer, 2017; Moeuf et al., 2018). Moreover, in different national programs, Industry 4.0 has been synonymously named as "Smart manufacturing", "Smart Production", "Industrial Internet" (Kamble et al., 2018; Oesterreich and Teuteberg, 2016; Thoben, 2017).

Reviewing the literature, different definitions of Industry 4.0 have been collected and reported in Table 2.1.

Source	**Definition**
(Brettel et al., 2014)	Industry 4.0 focuses on the establishment of intelligent products and production processes.
(Schmidt et al., 2015)	Industry 4.0 is the superposition of several technological developments that embraces both products and processes. Industry 4.0 is related to the so-called Cyber-physical systems that describe the merger of digital with physical workflows.

(Industrie 4.0 Plattform website)	Industry 4.0 refers to the intelligent networking of machines and processes for industry with the help of information and communication technology.
(Weyer et al., 2015)	In Industry 4.0, field devices, machines, production modules and products are comprised as CPS that are autonomously exchanging information, triggering actions and controlling each other independently.
(Lukač, 2015)	Industry 4.0 transfers the principles of the Internet of Things on the processing industry.
(Vogel-Heuser and Hess, 2016)	Industry 4.0 –derived from the German term Industrie 4.0– is used as a synonym for Cyber-Physical Production Systems (CPPS), i.e., Cyber-Physical Systems applied in the domain of manufacturing/production.
(Qin et al., 2016)	Under Industry 4.0, manufacturing will consist of exchanged information and controlled machines and production units acting autonomously and intelligently in interoperable.
(Tupa et al., 2017)	Industry 4.0 deals with the connection of all parts of machines via integrated data chains and operations.
(Kamble et al., 2018)	The term Industry 4.0 comprises a variety of technologies to enable the development of the value chain resulting in reduced manufacturing lead times, and improved product quality and organisational performance.

Table 2.1 – Industry 4.0 definitions

The above-mentioned definitions suggest that, in the Industry 4.0 scenario, the technologies allowing information communication and sharing play a crucial role in the construction of intelligent production processes, able to control and adapt themselves in relation to variable external conditions. However, in last years, a wider set of technologies emerged as relevant to transform a manufacturing system to finally succeed in the transformation towards Industry 4.0. In the next paragraph, such technologies will be discussed and classified.

2.2.1. The Smart Technologies

Industry 4.0 implies the implementation of advanced technologies that in most cases have been already embedded in conventional manufacturing systems. However, new ways in technology use and integration give birth to fully flexible and integrated manufacturing systems (Kagermann et al., 2013). At the basis of the ongoing Industry 4.0 paradigm, there are many foundational innovations involving not only machines but also sensors, workpieces, and IT systems connected throughout the entire value chain. Standard Internet-based protocols enable real-time interaction between devices and support data analysis to avoid and predict failures, as well as reconfiguration and adaptability capabilities (Cepin and Bris, 2017).

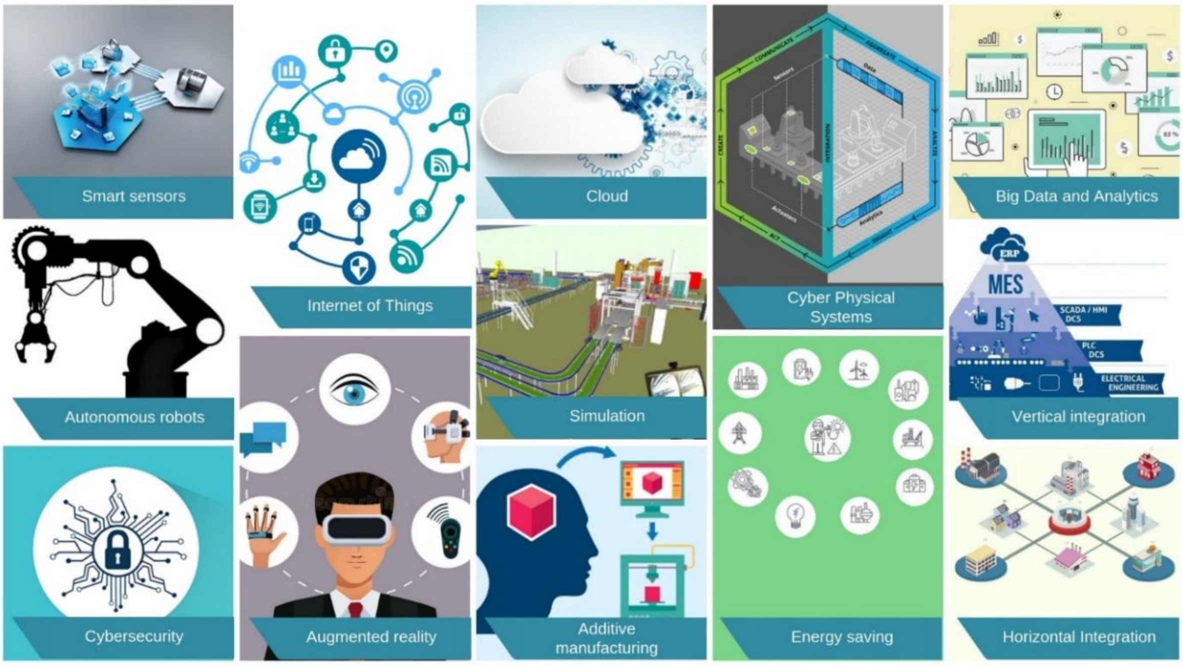

Figure 2.4 – Industry 4.0 KETs

In literature, different technologies have been recognised as pillars of Industry 4.0 and Smart Manufacturing. For instance, in the work of Mittal et al. (2017), based on a systematic literature review analysis, 38 enabling technologies are listed and clustered in 12 groups, according to similarities. For the purpose of this study, the most cited Industry 4.0 technologies represented in Figure 2.4, have been considered and reported in Table 2.2 with a brief definition and the sources that identify them as Key Enabling Technologies (KETs) for Industry 4.0.

Technology	**Definition**	**Source**
Cyber-Physical Systems	CPS integrate physical processes with computation capabilities and are able to operate in changing environments, maintaining a robust behaviour against unexpected conditions and failures (Lee, 2008). CPS create a network where intelligent objects can communicate and interact with each other and include computing and storage capacity, mechanics and electronics, and are based on the Internet as a communication medium (Schmidt et al., 2015).	(Kang et al., 2016; Lu, 2017; Mittal et al., 2017; Pereira and Romero, 2017; Shafiq et al., 2015; Trappey et al., 2016; Vogel-Heuser et al., 2015; Xu et al., 2018)

(Industrial) Internet of Things	Industrial Internet of Things (IIoT) enables the communication among every device inside and outside the factory. Zuehlke (2010) defines IIoT as a "non-deterministic and open-network in which auto organised intelligent entities and virtual objects will be interoperable and able to act independently pursuing their own objectives (or shared ones) dependently on the context, circumstances or environments".	(Kang et al., 2016; Lu, 2017; Mittal et al., 2017; Pereira and Romero, 2017; Rüßmann et al., 2015; Wang, Wan, Li, et al., 2016; Xu et al., 2018)
Big data analytics	Big data is characterised by volume, variety and velocity (the 3Vs), and it requires new techniques of data processing and analysis (Kang et al., 2016). Visualisation, analysis and sharing of data are at the basis of analytics that support decision-making and improve self-awareness and self-maintenance of the machines.	(Kang et al., 2016; Lu, 2017; Mittal et al., 2017; Rüßmann et al., 2015; Wang, Wan, Li, et al., 2016)
Cloud technologies	Cloud computing is related to the ICT-infrastructure that allows the ubiquitous access to data from different devices. Cloud can be treated as a service and support collaborative design, distributed manufacturing, collecting innovation, data mining, semantic web-technology and virtualisation (Park, 2013).	(Kang et al., 2016; Lu, 2017; Mittal et al., 2017; Rüßmann et al., 2015; Wang, Wan, Li, et al., 2016; Xu et al., 2018)
Cybersecurity	Cybersecurity strategies need to be developed in order to guarantee the security of the large amount of data collected, stored and communicated via IIoT (Khan and Turowski, 2016).	(Mittal et al., 2017; Rüßmann et al., 2015)
Virtual reality	Virtual reality is a computer interface that allows the user to be fully immersed in an experimental situation, i.e. a virtual environment, enabling the looking, moving and interaction of users in a world that is like the real one(Mujber et al., 2004).	(Frank et al., 2019; Mittal et al., 2017; Shafiq et al., 2015)
Augmented reality	Augmented reality (AR) allows the creation of a virtual environment in which humans can interact with machines using devices able to recreate the workspace. Interesting applications of AR are related to the training of workers	(Mittal et al., 2017; Rüßmann et al., 2015)

	and the support in manual production activities (Syberfeldt et al., 2016).	
Smart sensors	Smart sensors are traditional sensors embedded with intelligence capabilities, i.e. onboard microprocessors, which can be used for processing, conversions, calculations, and interfacing functions that can facilitate self-diagnostics, self-identification, or self-adaptation functions (Spencer et al., 2004).	(Kang et al., 2016; Mittal et al., 2017)
Simulation	Simulation tools can be widely used along all the value chain, starting from product design to operations management. Modelling and simulation tools are crucial for the development of digital engineering and virtual representation of products and processes, in order to identify in advance potential issues, avoiding cost and resource wastes in production (Mittal et al., 2017).	(Frank et al., 2019; Mittal et al., 2017; Rüßmann et al., 2015)
Additive manufacturing/ 3D printing	Additive Manufacturing (AM) consists in a cluster of technologies that enable to produce small batches of products with a high degree of customisation by adding rather than removing material from a solid block. The reduction of scrap material, a quicker market launch due to the rapid prototyping, higher production flexibility and a lower number of required tools are the major advantages of this technology (Horn and Harrysson, 2012).	(Frank et al., 2019; Kang et al., 2016; Mittal et al., 2017; Rüßmann et al., 2015)
Advanced robotics	The evolution of traditional robots opened the way to new collaborative solutions of robots (i.e. Co-Bots) that are able to work together with humans in a safe and efficient way. Moreover, embedded intelligence in robots can allow them to learn from human activities, improving their autonomy and flexibility (Thoben, 2017).	(Frank et al., 2019; Rüßmann et al., 2015)
Energy saving technologies	Energy saving technologies include monitoring and optimisation systems that allow reducing the energy consumption in manufacturing. Several energy decisions	(Frank et al., 2019; Kang et al., 2016; Mittal et al., 2017)

	tools (e.g. dashboards, apps) are provided to users to improve the energy management practices (Kang et al., 2016)	
Horizontal and vertical integration	Horizontal integration refers to the creation of a global value network through the integration and the optimisation of the flow of information and goods between company, suppliers and customers. The vertical integration, instead, is the integration of functions and departments of different hierarchical levels of the single company creating a consistent flow of information and data (Kagermann et al., 2013).	(Frank et al., 2019; Rüßmann et al., 2015; Xu et al., 2018)
Multi-agent technologies	Multi-agent systems (MAS) are organised sets of agents that represent the behaviour of objects of a system, capable of interacting and negotiate among them to achieve individual goals (Leitão, 2009).	(Lu, 2017; Park, 2013; Vogel-Heuser et al., 2015; Wang, Wan, Li, et al., 2016)

Table 2.2 – Industry 4.0 technologies

The introduction of Industry 4.0 technologies in industrial companies is highly context- and business-related, since different technologies can affect and improve different performances. In order to provide a more critical view on how these technologies are expected to change the manufacturing systems in the future (and consequently the human work in manufacturing), some data about their current implementation have been searched and are reported hereafter. In the Italian landscape, the statistics published by the Italian Ministry of Economic Development (Ministero dello sviluppo economico, 2018) report that the technology in which most of investments have been carried out is based on Internet of Things (Figure 2.5). High relevance is given also to all the technologies that allow data exchange, integration and analysis, while fewer adoption levels are related to simulation, smart materials and augmented reality.

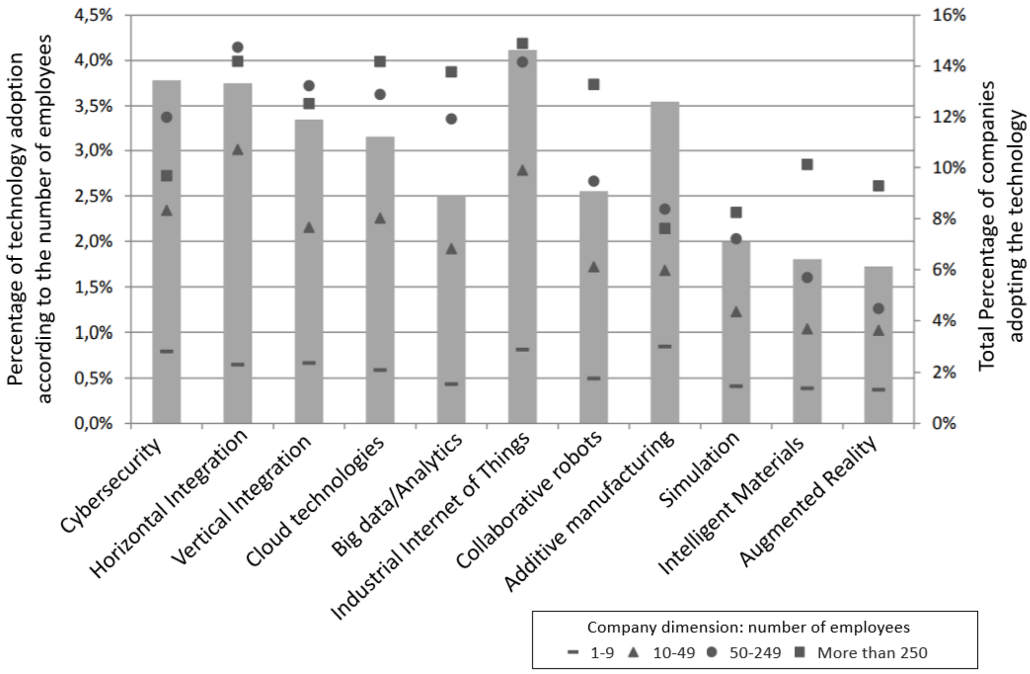

Figure 2.5 – Level of adoption of Industry 4.0 technologies in the Italian industrial context (adapted from Ministero dello sviluppo economico, 2018)

The same considerations can be made at European level, according to a survey conducted by the European Commission to explore the smart technology adoption in industry (European Commission, 2018). Also in this case, technologies related to data integration are the most relevant in the industrial implementation, and conspicuous investments have been done in last years to introduce big data & analytics, IoT, and cloud technologies (Figure 2.6). It is worth noticing that in the European survey the most widely adopted technologies are based on social media, which encompass all the digital tools used to keep in touch and strengthen relationships with customers. Social media are used at a more strategic and outbound level, thus not directly affecting the human work related to the operational management of smart factories.

As introduced previously, the adoption of these technologies in manufacturing systems significantly affects the environment in which humans work, and at the same time provide new capabilities to workers, bringing potentials to enhance their productivity and efficiency. Further exploration about the impacts of Industry 4.0 technologies introduction on human work in manufacturing will be presented in the next chapters.

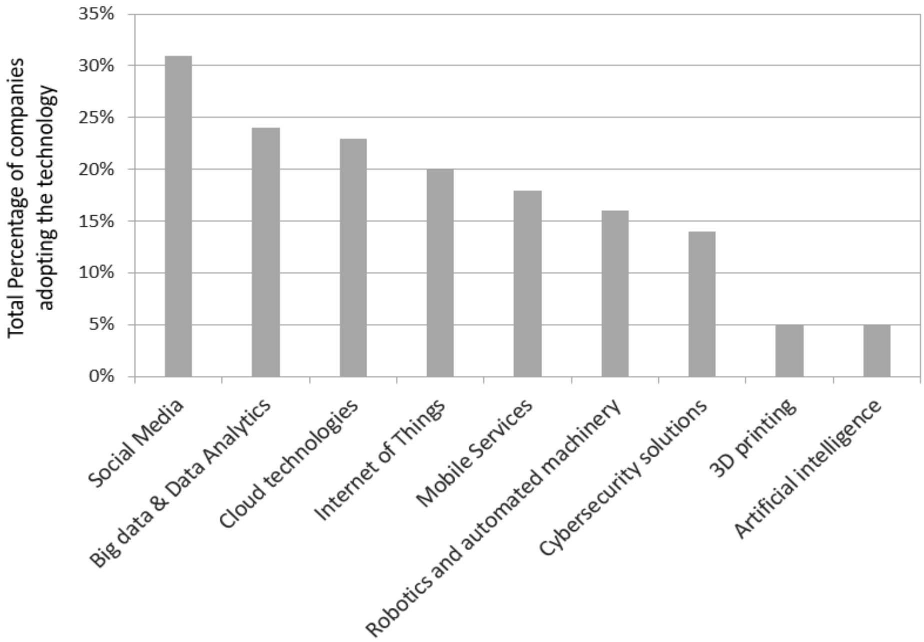

Figure 2.6 – Smart technologies adoption in Europe (adapted from European Commission, 2018)

2.3. The concept of Smart Factory and the design principles of Industry 4.0

The vision of Industry 4.0 spreads a new archetype in manufacturing industries, which is characterised by a new level of socio-technical interaction (Reimer et al., 2015). Each small and decentralised network is self-controlling and able to respond to different situations autonomously. The final characteristic of this new prototype of factory, the so-called Smart Factory, is the result of the convergence of the digital and physical world (Lee, 2015).

Beginning with a definition, Radziwon et al. (2014) propose the following: "A Smart Factory is a manufacturing solution that provides flexible and adaptive production processes that will solve problems that arise in a productive environment with changing conditions in a world of increasing complexity".

A Smart Factory can canalise and filter information, manage information overflow, and correct outdated information so that the right person can access the right information at the right time. It should provide human workers with a real-time information/fact-based decision support in production activities, resulting in an optimisation of the manufacturing process (Brettel et al., 2014; Davis et al., 2012; Lucke et al., 2008). This is achieved by systems working in the background that accomplish their tasks based on information coming from physical and virtual world. For example, information of the physical world could be position or condition of a tool, in contrast to information of the virtual world like electronic documents, drawings and simulation models (Lucke et al., 2008).

Products, resources and processes of a Smart Factory, compared with a traditional production system, provide advantages in term of quality, time, resource and cost. A manufacturing process based on CPS is automatically monitored, optimised, and thus able to respond to variations in real-time. The production revolution does not only regard innovation and cost-saving: it also gives birth to the concept of "bottom-up" production value creation model, because the adaptation and networking capacity of CPS can create new and more market opportunities, such as optimised individual customer product manufacturing (German Trade & Invest, 2014). A Smart factory encompasses several advantages that a traditional one cannot exploit, such as efficient use of the resources, machine adaptation to the human work cycle, and optimisation of the manufacturing processes.

According to Hermann et al. (2015), smart factories are the key feature of Industry 4.0, where IoT and CPS are employed and processes are integrated via IoS. More generally, six design principles are proposed, conceived to develop production processes aligned with the Industry 4.0 vision:

- *Interoperability.* Horizontal and vertical integration among different systems requires the creation of specific standards and protocols. Although some attempts of standardisation have been made by the German *Plattform Industrie 4.0* with the Reference Architecture Model for Industry 4.0 (Hankel and Rexroth, 2015), the definition of interoperability standards still represents an open research issue.
- *Virtualisation*. In CPSs, each physical asset is characterised by a virtual counterpart that is used to perform simulation and optimisation in a virtual environment (Lee et al., 2013).
- *Decentralisation.* If changes occur along with processes, distributed intelligence embedded in physical assets allows faster and more responsive corrective actions, facilitating decision-making processes, which can be managed at local level (Schoenthaler et al., n.d.).
- *Real-time capability*. The IoT enables real-time information flows, with the possibility to achieve real-time optimisation inside the processes (Hu et al., 2014).
- *Service orientation*. CPSs, together with cloud technologies, enable the implementation of service-oriented architectures, where computation capabilities can be accessed via the web, and process operations can be performed only when required by products through sensing technologies.
- *Modularity.* Advanced manufacturing solutions are conceived as modular, in order to be adapted to the different needs of the production. Reconfigurable Manufacturing Systems provide an example of a modular structure (Koren and Shpitalni, 2010).

The abovementioned features suggest that Industry 4.0 does not influence production processes exclusively from a technological point of view. Business processes require also a change of perspective to fulfil horizontal and vertical integration. Rather, the implementation of smart technologies and

Industry 4.0 proposes new paradigms in industrial management and engineering. The *German Plattform 4.0* discussed nine application scenarios (Plattform Industrie 4.0, 2016) to provide a specific focus on practical applications. In fact, each application scenario refers to a problem or a challenge, facing a user, through the description of the business background. In Table 2.3, the application scenarios are reported and discussed.

Application scenario	**Description**
Adaptable Factory	This application scenario refers mainly to the well-known concept of "*Plug-and-Produce*". This scenario largely describes the adaptability of a factory by physical conversion thanks to modularity, and this is particularly attractive for those companies whose orders are driven by product individuality and fluctuating demand.
Self-Organising Adaptive Logistics	This scenario can be considered as a logistics system that can function without significant intervention by humans, implementing more flexible and faster industrial and logistics systems, requiring more decentralised, agile and autonomously interacting materials-handling modules and reliable distribution logistics.
Value-Based Services	The key role of this scenario is covered by the IT platforms that collect data from product use, analyse and process these data to provide customised services, in order to strengthen customer loyalty.
Transparency and Adaptability of Delivered Products	Delivered products collect data autonomously for optimising business processes, for new business models and for a dynamic adaptation of product features. This application scenario describes the change in products that are becoming capable of adaptable design.
Order-Controlled Production	In this scenario, the company could adapt its own portfolio quickly – and, in particular, its production – to shorter and shorter innovation and product cycles, and make the best use of capabilities and capacities of existing production facilities ad-hoc according to the demand.
Operator Support in Production	Humans are assisted by increasing digitisation in industrial production. This increases motivation and productivity. Humans can assess increasingly complex situations, faster and carefully, giving more attention to the key factors and information on their tasks.

Smart Product Development for Smart Production	The key aspect of this application scenario is a collaborative product engineering. Virtual products allow new types of teamwork in engineering processes and automation of engineering activities.
Innovative Product Development	Several actors now cooperate in creating new and improved products as well as expertise, service and specialised technologies providers and product users. This is made possible by new forms of Internet-based cooperation.
Circular Economy	This application scenario describes how it is possible to circulate all materials used in products and manufacturing processes in closed biological and technological material cycles.

Table 2.3 – Application scenarios of Industry 4.0 (Plattform Industrie 4.0, 2016)

In industrial cases, real examples typically implement distinct aspects of several application scenarios (Plattform Industrie 4.0, 2016), while some of these scenarios can involve various areas of a company. This is the case of the *Operator Support in Production* scenario, which is the only one referring to the human aspects, but potentially affecting the engineering, the logistics, the production, the service and so on. While some application scenarios mainly refer to technological solutions to develop and design product and manufacturing processes in the smart manufacturing context, the *Operator Support in Production* poses more complex challenges that are related not only to the development of proper technology that can assist and support humans, but also to the changes that affect the human work in dealing with it.

Manufacturing companies are in different stages in their renovation process towards smart factories, and the demand for smart solutions depends upon several factors, such as their customers, stakeholders, markets, etc. One common aspect for all the firms is the need for cost efficiency, strictly related to the improvement of quality, flexibility and human labour. The implementation of such application scenarios, then, suggests that huge impacts, discussed in the next section, are expected.

2.4.The impacts of Industry 4.0 in manufacturing

It is believed that Industry 4.0 has a considerable impact on the industries and, especially, on the manufacturing ones, as there is a bigger necessity to handle high complexity and changes in demand towards more tailored products and modularised product designs (Brettel et al., 2016).

Indeed, the advent of Industry 4.0 involves different types of impacts on different areas of the manufacturing industry. Companies that integrate Industry 4.0 solutions can envision benefits such as revenue growth and cost reduction, also due to more efficient use of energy. Smart machines can be fully automated and can also support human work, and consequently workforce skills and requirements are changing. In the following, the main impacts of Industry 4.0 in manufacturing are presented, based on a critical elaboration of the insights offered by literature.

Productivity and efficiency

The increasing number of smart devices in the factory and the efficiency of the communication among them are favouring a global plant optimisation that results in an increase of the industrial productivity. In fact, collaborative productivity is allowed by the communication between people, between people and smart devices (HCI) and between smart devices themselves (M2M) (Schuh et al., 2013).

With the help of big data and M2M, the whole production process can be optimised: the average manufacturing routes are leaner, and the utilisation rate of resources is improved. Productivity is, indeed, enhanced thanks to the flexibility offered by the self-organisation attribute of smart machines, the ability to automatically reconfigure themselves to produce multiple types of products. The dynamic reconfiguration also brings robustness in the sense that new machines can join the system in a plug-and-play way (Wang, Wan, Zhang, et al., 2016), starting to work without the need for physical device configuration or operator intervention. Big data analytics can give an accurate knowledge of the production process and quantify performance indicators related to machines, products and systems. With the support of this information, the operator can plan the production easily and take more accurate decisions in a quicker way (Geissbauer, R. et al., 2016).

Business model

Companies that will update their business model, for example introducing new digital services based on data analytics will register progress in revenue growth. Thanks to the connection between products and services, but also to the horizontal integration between all suppliers along the supply chain, competitiveness will be ensured and additional revenues will be generated (Geissbauer, R. et al., 2016). The adoption of smart data analytics allows additional high-margin revenues: customised products and services usually generate significantly higher margins than mass-manufactured ones. The delivery of personalised solutions to final users according to their requirements is made possible by real-time data availability (Arnold et al., 2016).

Employment

As can be intuited, Industry 4.0 will have a significant impact on the employment. In the past, the high increase in the overall production volume was accompanied by a strong decrease in the number of manufacturing jobs. On the contrary, nowadays, the introduction of new products and services, enabled by smart technologies, is expected to bring new business opportunities on the market for companies and consequently to push the creation of new jobs (Boston Consulting Group, 2015).

In order to prepare for the change, companies, education systems, and governments must act in different ways. Prifti et al. (2017) suggest that companies will have to make some efforts starting from frequent retraining of the employees to keep pace with the introduction of technological advancements. The impacts of Industry 4.0 on the workforce have not been completely investigated yet, since they include several topics, such as competences, job profiles, human-machine integration and task allocation and they represent one of the most interesting and worth exploring topics in the Industry 4.0 research stream.

Sustainability and energy efficiency

Smart manufacturing aims at integrating all the aspects of manufacturing with the purpose of achieving superior control and productivity. When an investment improves the productivity of a process, facility, workforce or company, it also tends to save energy. Energy efficiency plays a central role in the manufacturing process and it is an objective for industrial enterprises for different reasons: economic, environmental and political. The reduction of energy consumption of machine tools implies improvements in the environmental performance of manufacturing processes and systems.

Energy is a variable cost of production representing a substantial portion of operating cost; therefore, it is a key factor for companies that aim to the productivity maximisation and the costs' minimisation. Experts in the field of manufacturing automation forecasted a 20 per cent reduction in energy intensity for each company (American Council for an Energy-Efficient Economy, 2013).

Quality management

Industry 4.0 offers great opportunities in the field of quality management mainly due to its key aspects: vertical integration, horizontal integration, and end-to-end engineering production (Kagermann et al., 2013). With vertical integration, all the devices belonging to the different production steps are connected, making available useful information to monitor the performances and to regulate processes in real time. In case of quality deviations, caused by a malfunctioning in the machines, sensors immediately notify the issue so that the responsible person can rapidly identify and repair it. Horizontal integration allows the customer to get the current status of the product at any time. Finally, engineers can analyse the behaviour of the products anytime and make changes quickly (Zhou and Piramuthu, 2012).

Supply chain management

Thanks to the combination of internet technologies with the flow of information and self-controlling smart machines and smart products, the supply chain will be fully integrated, supported by interconnected systems, and perfectly coordinated. All those factors will bring cost reduction opportunities, an increase of process transparency, optimisation of the procurement process, and flexibility, in particular in the procurement, production and distribution stages. In "Procurement 4.0"

(Glas and Kleemann, 2016) smart systems are able to determine the demand for a certain material and generate an order that is autonomously transmitted to the supplier without any necessary human interference. Also, distribution activities are characterised by a significant degree of automation that implies autonomous decision-making, controlling, planning of logistics activities (Broy et al., 2012).

Engineering

As hinted before, End-to-end system engineering (Kagermann et al., 2013) allows a more flexible and customised product and process development, giving the opportunity of shorter development periods, individualisation of products and new approaches in product-service development, such as open innovation, product intelligence or product memory (Lasi et al., 2014). In addition, thanks to virtualisation and digitalisation, concurrent engineering is enhanced and the simulation of products and processes in the virtual environment help engineers and technicians in anticipating problems and errors that could occur when deploying new products and processes (Tolio et al., 2013). Finally, the feedback from the utilisation of products can allow continuous improvement (Schmidt et al., 2015).

2.5.The business transformation towards Industry 4.0

According to McKeown and Philip (2003), "*transformation is not just about reducing costs, improving profitability, or re-engineering. Transformation is the invention of strategies and management processes. It must be driven by new ideas, a new concept of opportunity*". The process of business transformation, then, could occur in different ways, through a multi-stage implementation or by a holistic model. In any case, a great effort and a strong commitment are required and determinant for a successful transformation (Cowan-Sahadath, 2010).

Applied to the Industry 4.0 context, the business transformation process addresses different topics. Actually, the Industry 4.0 paradigm has opened high potentialities to implement new business and operational models. Many manufacturing companies around the world have been encouraged to invest in research and industrial projects to enable the realisation of smart factories (Kang et al., 2016; Qin et al., 2016; Thoben, 2017). In this context, several technology providers have started offering products and product-service systems (PSS) solutions based on key enabling technologies that have achieved a stable and mature phase of their lifecycle, i.e. IoT for data acquisition and transfer, autonomous and collaborative robots, IT platforms for big data (Geissbauer, R. et al., 2016). Despite this, many customers (i.e. manufacturing companies) are still restive to change their production processes to be Industry 4.0-compliant. There are several implementation barriers for smart manufacturing, not exclusively technology-related. The main issues refer to the business process transformation of manufacturers, and include, among others, organisational impacts and employees skills (Prifti et al., 2017). Further, some barriers depend on companies' business models and on their positioning in the supply chain.

2.5.1. The new paradigm of collaborative operating processes

To understand the business transformation that will involve the factories of the future, it is necessary to study in-depth the changes in business processes, as proposed by Industry 4.0 paradigm. The Industry 4.0 is a wide and global vision, involving the whole manufacturing environment, proposing new perspectives for business processes too. Thanks to the connectivity offered by IoT, a manufacturing process can be seen as one of the main elements of a more complex system (Figure 2.7). Here, the factory is one of the crucial points for data generation, while data exchange is always bidirectional, making suppliers, customers, transportation systems and employees fully integrated and relevant for the optimisation of the whole system. In such a context, the network of stakeholders, products and equipment, allows an end-to-end engineering integration along the value chain (Stock and Seliger, 2016), while five value creation factors - products, processes, equipment, humans and organisation - can be identified, and thus properly managed by companies to undertake the Industry 4.0 transformation.

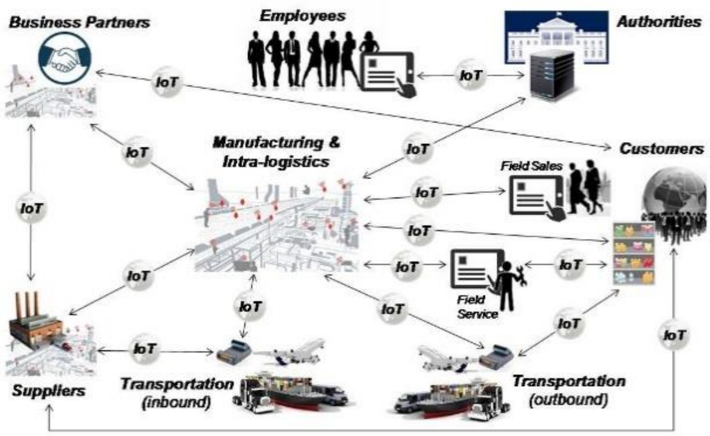

Figure 2.7 – Business scenario of Industry 4.0 (Schoenthaler et al., 2015)

Products become smarter because they have embedded sensors and identification technologies (Qin et al., 2016). They can do computations and communicate with the environment, providing their identity, state and properties (Schmidt et al., 2015). To communicate with these smarter products, the equipment and the processes have to change. Indeed, the factory becomes conscious and intelligent enough to make decisions at decentralised level and in real time about machines maintenance and production control (Qin et al., 2016). Also the work organisation changes, moving to "human cyber-physical system", defined by (Romero, Bernus, et al., 2016) as a "system engineered to (a) improve human abilities to dynamically interact with machines in the cyber- and physical- worlds by means of ‘intelligent’ human-machine interfaces, using human-computer interaction techniques designed to fit the operators’ cognitive and physical needs, and (b) improve human physical-, sensing- and cognitive capabilities, by means of various enriched and enhanced technologies (e.g. using wearable devices)”. Finally, relevant impacts at organisational level emerge. In particular, among the all competences identified as relevant for Industry 4.0, technological skills, mainly related to the use of data analysis and IT, as well as behavioural competences (i.e. teamwork, collaboration, negotiation), have cross importance to succeed in an Industry 4.0 context (Prifti et al., 2017).

Considering all these aspects at the same time makes the process of business transformation very complex and challenging for companies, that are expected to align their business strategy with the vision proposed by the smart manufacturing paradigm.

Some models to support the Industry 4.0 business transformation have been proposed in literature (Bücker et al., 2016; Erol, Schumacher, et al., 2016; Ghobakhloo, 2018). They all highlight as main aspects: i) the need of a clear idea of the aims each company wants to achieve exploiting new technologies; ii) the involvement of all the partners that can take part in the transformation (that is, not only the management but also customers, suppliers); iii) the formulation of specific roadmaps to translate long-term strategies into practical areas of development, also with the support of readiness assessment models and maturity models (Rockwell Automation, 2014; Schumacher et al., 2016) able to identify companies’ strength and weaknesses; iv) the development of pilot projects, including either technological or organisational and infrastructure projects, in order to identify improvements and real advantages, to extend pilot projects at large scale, transforming them into operational standards.

2.5.2. Different perspectives on business transformation

The optimal path of business transformation towards Industry 4.0 is highly affected by different company’s features and position in the supply chain. Suppliers, technology providers, and machines /equipment manufacturers (suppliers for short) can be characterised by sophisticated PSS business models, where the product offering is bundled with services, support, self-services and knowledge (Baines et al., 2009). Customers and users, instead, are usually manufacturing organisations using the technologies in their processes. Thus, suppliers embed the technology in their products-services, whereas the customers use the technology to make their processes more efficient and high-performing. Being the technology one of the main drivers for Industry 4.0 transformation, this differentiation strongly affects the opportunities that smart manufacturing introduction can bring to companies.

Also the other drivers of the transformation (e.g. product, processes, organisation, governance) (Schumacher et al., 2016) can be related differently to the two perspectives of suppliers and customers. In addition, the expected impacts of Industry 4.0 in terms of measurable key performance indicators (KPIs) are not the same. While suppliers can benefit of major revenues for the increasing offering of digital solutions (made of services and products), customers can gain efficiency from a real-time controlled production, able to manage changes and predict failures and issues potentially generating downtimes or quality problems. All the aspects discussed above are presented in Table 2.4.

	Business opportunities	KPI	Challenges
Suppliers	New digital business models	• Increasing of sales revenues from added services on products • New sales revenues from platforms and cloud-based services	• Privacy issues in sharing data with external stakeholders • Investment in integrated digital tools • Business partners not able to collaborate around digital solutions • Lack of digital skills in the workforce
	Digital engineering	• Reduced time to market, thanks to the availability of integrated digital tools for product development • High-level information from field for R&D improvements	
	Digital sales and marketing	• Better customer relationship with the possibility to offer personalised products/services	
Manufacturers	Vertical operations integration	• Faster decision-making • Improved quality, with real-time process control • Increasing of energy efficiency	• Investment in infrastructures for machines' connections • Cultural transformation to manage operations using digital technologies • Economic benefits and return on investment more difficult to estimate
	Horizontal integration	• Lower transport and logistics costs, due to real time supply chain optimisation • Lower warehousing costs and spare parts management costs	
	Smart maintenance and service	• Preventive maintenance, thanks to real-time information from the field • Increasing of asset utilisation and availability	
	Digital workplace	• Better and faster training for operators • Increasing of productivity	

Table 2.4 – Supplier and manufacturers perspectives

However, for the suppliers the transition towards Industry 4.0 is mainly supported by technological improvements, allowing them to develop their strategies by offering advanced PSSs. Here, the main challenges concern the acquisition of new technical competences, mainly to be used in R&D and IT departments. On the contrary, the most relevant business opportunities for customers involve operations management, for instance maintenance and quality practices or logistics issues. Also the workforce at the lowest level is involved, making the path to smart manufacturing more difficult (McKinsey Digital, 2016), due to the complexity in acquiring technical competences about IT infrastructure and data management, coordinating actions among different departments, defining new practices in operations management, and estimating the return on investments.

Thus, it appears clearly that for both suppliers and manufacturers the workforce involvement in the business transformation towards Industry 4.0 is crucial, suggesting that new collaboration mechanisms and interactions between humans and technologies will be the key to succeed.

Such considerations call for the necessity to deeper investigate the role of the human factor in the context of Industry 4.0, in order to provide proper advice about the design of new jobs and workplaces for the factories of the future.

2.6.Reference models for Smart Manufacturing

To conclude the literature overview about Industry 4.0, the reference architectural models for smart manufacturing are discussed. In literature there is still a lack of a common and clear framework describing what the whole architecture of a smart manufacturing system should be. Some reference models have been proposed, but, in most of the cases, they are focused on a specific issue, such as the informative system or the automation and control process.

The first structured description and reference model of the Industry 4.0 concept is reported in the final report of the *German Plattform Industrie 4.0* (Kagermann et al., 2013), where the Industry 4.0 description is contained in a wider vision, in which the smart factory is only one of the parts of a completely connected world. In such a complex system, the Internet of Things and Internet of Services (IoS) enable the communication and the sharing of information outside the smart factory, while inside, the key technology that transforms the production process into smart processes is CPS. In Kagermann, Wahlster, et al. (2013), the Industry 4.0 model is based on three key features already discussed in paragraph 2.1: horizontal integration through value networks, vertical integration and networked manufacturing systems, end-to-end digital integration of engineering across the entire value chain. After 2013, many different models have been proposed, in most of the cases trying to describe how to achieve the three integrations suggested.

1. A first class of models describe the **Industry 4.0 architecture based on CPS**. Monostori (2014) defined the concept of Cyber-Physical Production System (CPPS) as a group of “autonomous and cooperative elements and sub-systems that are getting into connection with each other in situation-dependent ways, on and across all levels of production, from processes through machines up to production and logistics networks”. To implement such kind of system, Monostori suggests surpassing the traditional automation pyramid in favour of a decentralised model with multiple interconnections among objects (Figure 2.8).

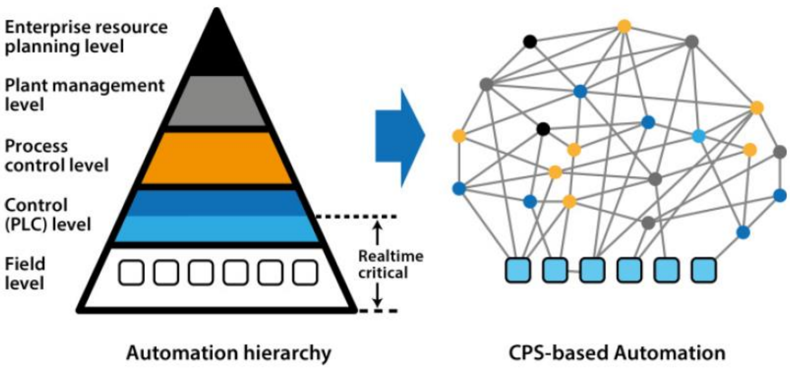

Figure 2.8 – Decomposition of the automation hierarchy with distributed services (Monostori, 2014)

The pyramidal model refers to the enterprise-control system architecture standardised in the IS/IEC 62264 and ISA 95, in which hierarchical information flow is suggested from the field level (sensors) to the ERP, through control systems such as PLCs and supervisory systems, e.g. SCADA (Chen, 2005). This perspective embraces all the three features of integration previously discussed. The connected objects of a CPPS could be humans, products, machines, etc. The entire system could be a production process, a supply chain, a development process. In every context, the characteristics expected from the system are reliability, self-organisation and self-repair, predictability, interoperability and tracking capabilities.

Another architecture proposed in literature, which assimilates a smart manufacturing system to a CPS, is the Lee pyramidal model (Lee, Bagheri, et al., 2015). It reuses the automation pyramid from a different perspective, introducing the new capabilities offered by the CPS in the use of field data for self-optimisation. The Lee's 5-C architecture (Figure 2.9) describes the way from data acquisition to value creation. The lowest level represents the data acquisition, performed by smart sensors. The data acquired, then, are processed in the second level, trough machine learning techniques, to perform diagnostics and prognostics about the system. The third level represents the collection of the information converted in the previous level from different kind of machines or processes. At this level, comparisons are made among clusters of similar machines, in order to make every process aware of its state, by comparing it with other similar ones. The fourth and the fifth levels refer to the highest elaboration of processes information, performing analytics and supporting decisions, considering the knowledge created by the previous stages.

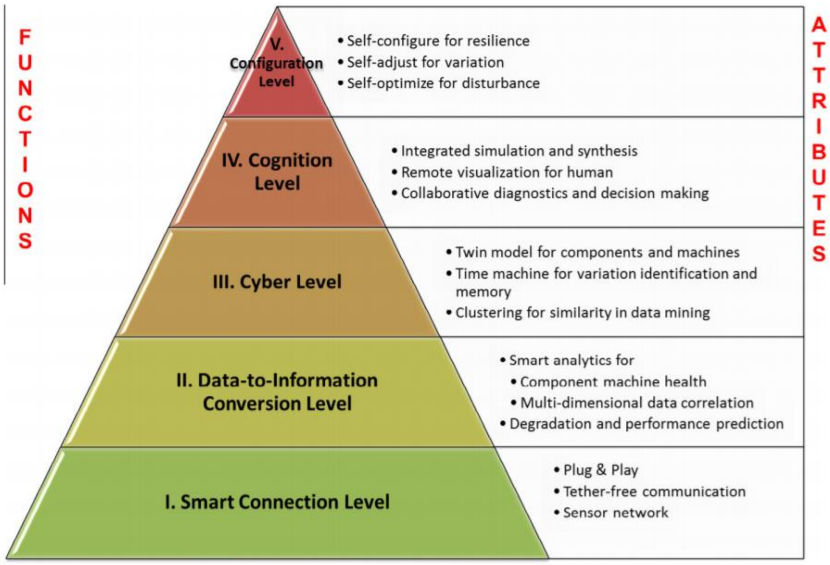

Figure 2.9 – 5-C CPS architecture (Lee, 2015)

The focus of Lee's model is on vertical integration inside a single production process. In other works, Lee proposes this architecture supporting prognostics and health management for improving maintenance strategies (Lee, 2015; Lee, Bagheri, et al., 2015; Lee and Bagheri, 2015).

Opposite to this model, (Mosterman and Zander, 2015) have suggested another framework for designing intelligent manufacturing systems based on CPS, which is more focussed on the horizontal integration of different objects with distributed intelligence. In this work, a practical study is reported to represent collaborative systems that communicate in real-time. In the paper, the authors developed a demonstrative system in which the activities execution sequences are proposed by the intelligence embedded in the elements being worked. All the functioning of the system is based on the synchronisation of the shared resources, and communication and control are fundamental.

Another interesting perspective about CPS and smart factory has been proposed by Shafiq et al. (2015) with the concept of Virtual Engineering Object/Virtual Engineering Process (VEO/VEP) as a specialisation of CPS for the Industry 4.0 (Figure 2.10). In this work, the manufacturing system is associated with its virtual representation, where all the real objects have their digital counterpart in a virtual environment. The virtual representation of objects and processes contains all the knowledge and the experience about them, so it fits with the representation of CPS as an embedded system that provides intelligent capabilities to a physical object/process. According to the authors, the virtual model features could satisfy the requirement of interoperability, virtualisation, decentralisation and real-time capability, which are at the basis of the CPS design and VEO/VEP can be used as a reference model to develop

Industry 4.0 processes. In the paper, a detailed description of the VEO/VEP characteristics that fit with the three kinds of integration proposed by the Kagermann is reported. Moreover, it suggests that the virtual representation of objects could be assimilated to a CPS, while the VEP is most suitable for the production process representation in CPPS. Therefore, the VEO/VEP perspective can be used, according to Shafiq et al. (2015) to conceive a smart manufacturing system with self-organising production and control strategies.

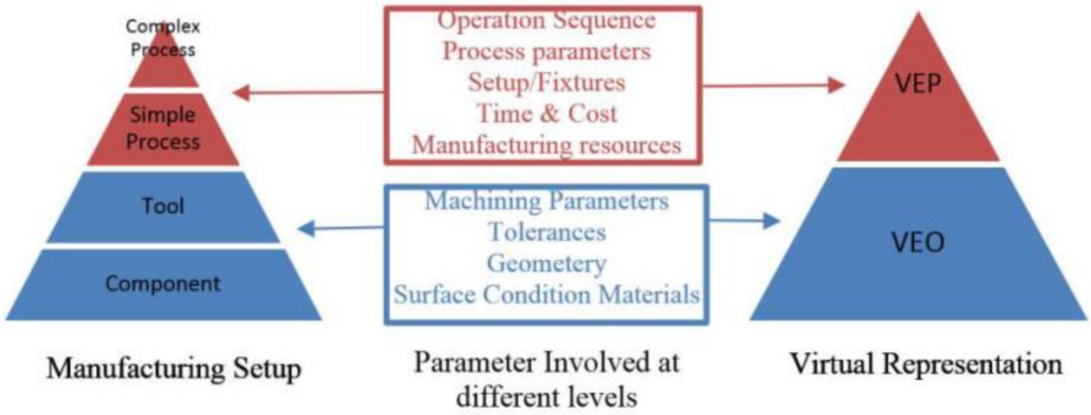

Figure 2.10 – Correlation between physical and virtual world (Shafiq et al., 2015)

2. A second group of models concerning the Industry 4.0 regards more in detail the **IT properties** required for creating integration inside and outside the smart factories. (Mazak and Huemer, 2015) focus on the horizontal integration among enterprises. The requirement that is envisioned as necessary is interoperability, and available standards for data exchange are analysed first. The suggested framework aims at identifying the appropriate standards for Industry 4.0 context through a classification along three dimensions. The first dimension distinguishes between strategical/tactical and operation layer, in order to identify the languages that are proper for the description of business and operational functions responsible for value creation. The second dimension distinguishes between processes that are internal to the enterprise (e.g. production) or external (e.g. procurement). The third dimension distinguishes between the business operational view (BOV), which is composed of rules and tools used for describing the business aspects of the data exchange, and the functional service view (FSV), which concerns the technical implementation of IT standards (Open EDI standard, ISO/IEC 14662, 2010).

The model suggested by (Theorin et al., 2016), on the contrary, provides an architecture for achieving vertical integration inside the manufacturing system. The Line Information System Architecture (LISA, Figure 2.11) is an event-driven architecture in which every object can send messages to each other when an event occurs. For instance, the events can represent an operation performed by a worker or a machine cycle. The strength of the LISA is that the communication is enabled by different kinds of endpoints, capable of catching information from several interfaces and protocols and converting them in the standard LISA format. For instance, the data acquired from the in-field devices (e.g. sensors) could be transferred as simple bits to the endpoint, which is a customised software adapter, able to transform the bits coming from different devices into LISA-compliant variables.

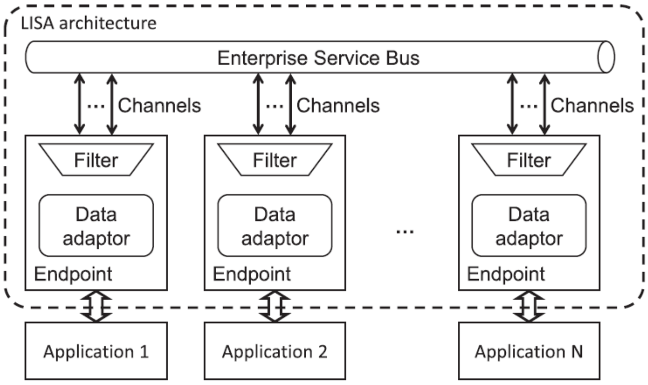

Figure 2.11 – LISA architecture (Theorin et al., 2016)

3. Finally, a third class of models have been conceived, in order to support the standardisation issues of Smart Manufacturing.

   Within the German *Plattform Industrie 4.0*, a group on reference architecture, standards and norms was established with the contribution of DIN (German Institute for Standardisation) and DKE (German Commission for Electrical, Electronic and Information Technologies). In this context, in April 2015, the **Reference Architecture Model for Industry 4.0** (**RAMI 4.0**, Figure 2.12) has been proposed. The RAMI 4.0 has been developed starting from the Smart Grid Architecture Model (SGAM), which was defined by the European Smart Grid Coordination Group to enclose and position all the standards available in different fields and describe the interoperability and the information exchange in smart grids. To adapt this framework to the Industry 4.0, the SGAM has been enriched with components that are distinctive of the industrial production, and, finally, the RAMI 4.0 architecture has been defined as a three-dimensional structure.

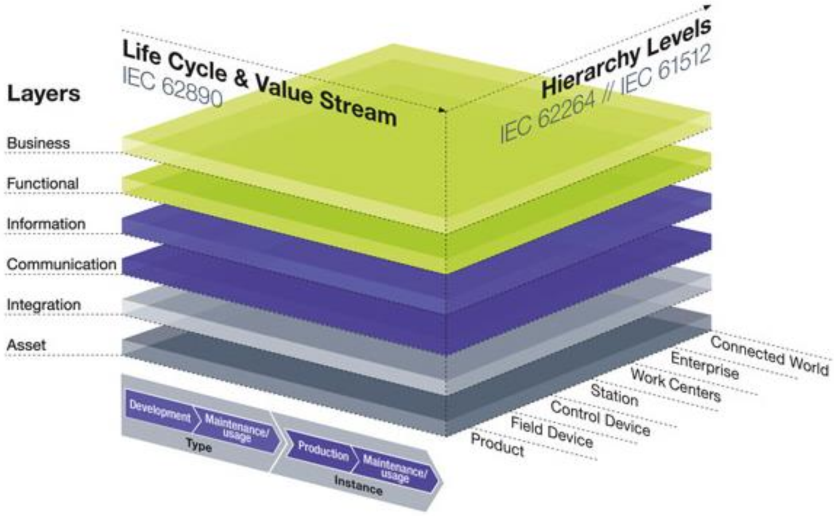

Figure 2.12 – Reference Architectitecture Model for Industry 4.0 (Plattform Industrie 4.0)

The first horizontal axis represents the value chain and the lifecycle, introducing the difference between type and instance for every component of the industrial scenario, as a machine, a product, a plant. The fundamental distinction is that a type is the general concept of a component when it is projected in the development stage. A type is a theoretical concept, a plan and it involves the steps from design to testing. A type becomes an instance when it is created in the real world and can generate many different similar instances, with their own lifecycle. The other horizontal axis represents the different hierarchies of a production system, in accordance with IEC 62264 and IEC 61512 standards. Elements like control devices, workstations, enterprises are common for any system, but in addition, the RAMI 4.0 introduces two novelties: the connected world on one side, to represent the network between enterprises, and the product on the other side, to comprehend the need of smarter product, able to communicate with the entire system. Finally, the vertical axis is composed of six layers, which describe various perspectives such as physical world (asset), integration of software and hardware, communication capabilities, functional properties, information creation through data and business processes. We can say that the six layers are the IT representation of an Industry 4.0 component, which consists on an object and its administrative shell that contains the virtual representation of the object (Halilaj et al., 2016). The administrative shell provides interfaces for compliant communication, identifiability, virtual description of features and services (Hankel and Rexroth, 2015).

In parallel with the German initiatives, in May 2015, in the U.S. the Industrial Internet Consortium developed the **Industrial Internet Reference Architecture** (IIRA, Figure 2.13), a model based on the ISO/IEC/IEEE 42010:2011 standard, in which the focus is on the properties of a system, as they are perceived by different stakeholders involved (Lin, 2015). Stakeholders in this context include system users, operators, owners, vendors, developers, and technicians who maintain and service the systems. The IIRA is a set of layers that represent the perspectives of the stakeholders, referred to as viewpoints: business, usage, functional, and implementation. Each layer of the IIRA contains a collection of issues interesting for the different stakeholders. In the proposed architecture, these issues are called "concerns" and the IIRA aims at underlining that many different topics of interest about the same system emerge if we consider the perspective of different roles that are involved in the system design and usage. In the business viewpoint, for instance, there is the definition of all the functions required to the system in order to support strategic business objectives. The stakeholders interested in these topics are the managers and the system engineers. From the opposite side, in the implementation viewpoint, technological aspects, such as connectivity and data storage are taken into account and the component developers and integrators are the interested stakeholders.

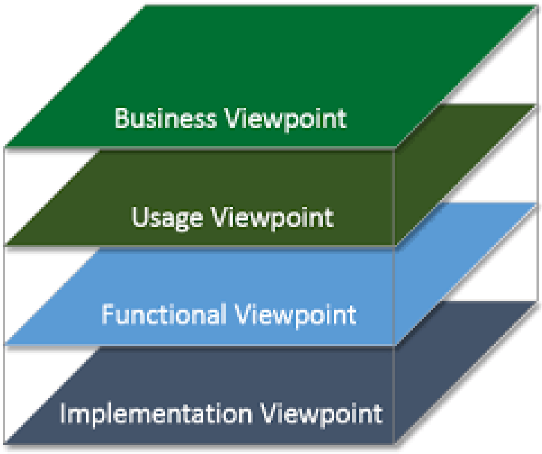

Figure 2.13 – The Industrial Internet Reference Architecture (Lin, 2015)

Concurrently, other reference architectures have been proposed (Takahashi et al., 2017; Weyrich and Ebert, 2016). An interesting analysis of the dimensions and sub-dimensions considered in such models and architectures is provided by (Li et al., 2018). In Figure 2.14, a comparison among different models (including e.g. RAMI 4.0 and IIRA) is presented.

Dimension	Sub-dimensions	SME	RAMI4.0	IMSA	IVRA	IIRA	F-CPS	IoT-ARM
Business / Management (domains, technology revolution)	System Hierarchy	x	x	x	x	x		
	Product Lifecycle	x	x	x	x	x	x	x
	Business (Supply Chain) Lifecycle	x	x	x	x	x	x	x
	Production Lifecycle	x	x	x	x	x	x	x
	Manufacturing Mode Development							x
Industrial Technology Revolution	New Equipment		x	x	x			
	New Manufacturing Process Techniques		x	x	x		x	
	New Energy				x			
	New Materials				x			
Information Technology Revolution	Function Layers	x	x	x			x	x
	Communication Technology Development		x	x	x	x	x	x
	Network Technique Development		x	x	x	x		x
	Data Storage Technology Development					x		x
	Database Technology Development		x	x				x
	IT Infrastructure Development		x	x	x	x		x
	CAX / Simulation Technology Development	x	x					
Human / Organization Promotion	Organization Management Scope	x	x					
	Human Resource Talent Levels				x			
	Capability / Performance	x			x			

Figure 2.14 – Dimensions and sub-dimensions of Reference models and architecture for Smart Manufacturing (Li et al., 2018)

From the comparison, it appears clearly that the dimension that has been less considered is the Human/Organisation promotion.

Being the focus of all the presented models mainly on standardisation and communication among different systems inside the enterprise, the role of the humans in the Smart Manufacturing environment has not been clarified yet. Human capabilities related to Industry 4.0 as well as the interaction mechanisms of humans with technology has not been properly formalised and included in general frameworks as the reference architecture models presented. To cover this gap, only a socio-technical perspective can provide a contribution to identifying the role of humans in Industry 4.0. Indeed, looking for frameworks able to jointly address the technological and human aspects, socio-technical system theory has been identified as suitable and in particular a socio-technical model named HTO has been already used in literature in the Industry 4.0 context. For this reason, in the next paragraph, the socio-technical systems and the Human-Technology-Organisation concept will be further explored and discussed.

2.7.HTO concept for smart manufacturing

The coexistence of technology and human factors in the manufacturing makes it possible to identify the smart factory environment as a Socio-Technical System (STS).

The socio-technical concept arose in the 1950s during the first action research projects of the Tavistock Institute in the British coal mining industry (Trist, 1981), aiming at analysing how new forms of work organisation emerged after the introduction of evolved technical conditions. The researches of the Institute paved the way to a new “paradigm of work”, in which the requirement of the social and technical systems needed to be merged to design efficient organisations (Emery et al., 1978).

In fact, in a STS, "social and technical elements must work together to accomplish tasks" and the "work systems produce both physical products and social/psychological outcomes" (Appelbaum, 1997). The socio-technical approach consists in merging the two perspectives of technical (i.e., tools, equipment and processes) and social systems, composed of people and their relationships (Hadid et al., 2016). The STS concept could be appropriately associated with the smart factory context, in which the interaction between humans and technology turns out to be essential as well as critical (Stern and Becker, 2017). Actually, in a socio-technical production system, several interrelated elements can be recognised (e.g., people, technology, processes, infrastructure, etc.) and conceptual models have been provided in literature to describe the relationships among them (Davis et al., 2014). To fit the Industry 4.0 socio-technical scenario, some authors proposed the Human-Technology-Organisation (HTO) descriptive model represented in Figure 2.15 (Bücker et al., 2016; Dombrowski and Wagner, 2014; Dregger et al., 2016).

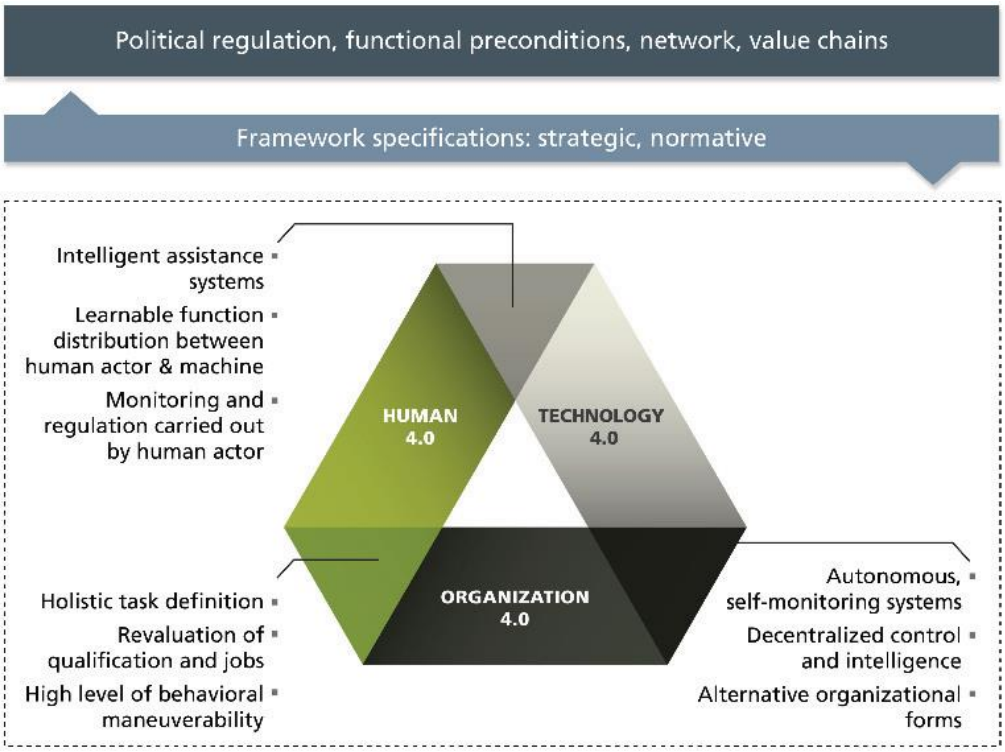

Figure 2.15 – Human-Technology-Organisation Model for Industry 4.0 (Dregger et al., 2016)

Generally, the HTO model aims at describing the functioning of a system through the interaction of the three subsystems, as defined by Karltun et al. (2014) and reported in Table 2.5.

Subsystem	Description
Human	1) A biological energy processing system; 2) an information processing system; 3) a psychic subject with a unique history and 4) a member of social groups and cultures
Technology	Means for the transforming of input to output using artefacts, procedures, and methods including know-how
Organisation	Consciously coordinated social entity, with a relatively identifiable border, which is relatively continually working for reaching common goals

Table 2.5 – HTO subsystems definition (Karltun et al., 2014)

Such a scenario suggests that proper integration among the three subsystems must be achieved to reach suitable performances of the whole system.

Concerning Industry 4.0, the topics pertaining to the three interfaces between the subsystems can be described as follows.

- The Human-Technology (HT) interface concerns the design of human-oriented systems, to ensure proper communication and collaboration among operators and technological systems, namely machines, but also the development of intelligent assistance systems. Indeed, in Industry 4.0 production systems, human and technology cooperate and a proper task division and organisation among them is crucial.
- The Technology-Organisation (TO) interface encompasses all the aspects related to the organisational design of the new smart manufacturing systems. Therefore, the impacts of technology on organisational variables are considered. The TO interface also concerns the analysis of the decision-making processes that occur in a smart factory, in order to provide suitable work design models.
- The Human-Organisation (HO) interface is related to the changing role of workers in the organisations in the context of Industry 4.0. New competences are required to workers and new roles and figures are emerging in companies, posing several challenges in terms of education and training.

For each of these interfaces, technological and methodological research issues along with implementation matters arise, suggesting that further investigations are needed to properly design the manufacturing processes of the future.

3. RESEARCH OBJECTIVES AND METHODOLOGY

3.1.Gap analysis about Human Factor in Industry 4.0

According to the previously discussed literature, in next years, Industry 4.0 is expected to change substantially the manufacturing paradigm.

A common factor characterising the above-presented literature is the techno-centric perspective, where the technology advancements represent the main trait of Industry 4.0. Although this is undeniably true, it is also important to underline the impact of this new paradigm on the company at large. Indeed, changing the technological landscape in a company affects the people working in the company itself. As a result, the introduction of the Industry 4.0 paradigm poses a set of challenges, beyond the technological implementation, concerning the operational, organisational and managerial levels, which has to cope with the digital transformation. In other words, implementing Industry 4.0 technologies presents not only scientific and technological challenges but also social and political issues (Zhou et al., 2015), since the proposed paradigm shift significantly impacts on the human work as well. Since the beginning of industrial production, humans have played a fundamental role, which over the years has changed, thanks to technological innovations that have relieved operators from tasks and activities considered dangerous and/or extremely heavy, allowing them to cover more and more roles of supervision and control of manufacturing systems. In this regard, despite Industry 4.0 is characterised mainly by digitalisation and advanced automation, the human role inside a smart manufacturing system is expected to remain dominant (Jäger and Ranz, 2014).

Technology and human factors, then, are purposely tied in the manufacturing sector. In the scientific literature, it has been noted that approximately the 50%-75% of implementations of new technologies have failed (Chung, 1996) for problems concerning aspects related to the human component (Lewis and Boyer, 2002). Indeed, each technical or industrial system needs to consider that humans are involved at some point. The interdependent relationship between advanced technologies and humans in manufacturing has been postulated also by Mital and Pennathur (2004).

However, in the Industry 4.0 research agenda, all the main aspects concerning the human factors have been widely neglected by both academic researchers and industry. Kinzel (2017) highlights that, according to a simple literature analysis on the Scopus database, humans have a marginal role in the literature on Industry 4.0. In addition, the macro perspectives about smart manufacturing appear to work entirely without the human intervention. This is strictly connected with the previous analysis of the reference models for Industry 4.0, which scarcely consider humans (see par. 2.6).

Only recently, recognizing the importance of considering the human factor in the transformation towards the Industry 4.0 paradigm, the governments of Germany, France and Italy, revised the main aspects of Smart Manufacturing, adding the *Human being* to the three kinds of integration envisioned in the first definition of Industry 4.0 (i.e., horizontal, vertical, end-to-end engineering integration) (Plattform Industrie 4.0, 2018).

The relevance of humans in the transition to Industry 4.0 requires a clear understanding of how humans can be part of a smart manufacturing system, which are the technology-human interactions and how these systems can be designed considering the human factors.

Several fields of investigation can be explored, since humans are involved in the Industry 4.0 in two main roles: i) they are users, that is they will be supported by technology in many manufacturing activities; ii) they are designers, that is they are required to envision and project the manufacturing systems of the future always considering the human factors.

For all these reasons, the research concerning the human factor in Industry 4.0 can be considered of utmost relevance. In particular, based on the literature review and the previously discussed issues, three main gaps have been identified.

1. **How human tasks are affected by Industry 4.0 technologies**

   Changes in the organisation of tasks between humans and technology are likely to occur and proper integration between human and technology capabilities will be the key to success in the transformation towards Industry 4.0. The introduction of new technologies will inevitably change the work of operators. In particular, it is possible to argue that technology will replace some tasks that are usually performed by humans, but, at the same time, new tasks will appear. Similarly to the past, also in the Industry 4.0 context, some researches aimed at exploring how automation could replace the human tasks, proposing different models to evaluate the most convenient task allocation between machines/robots and humans (e.g., Bruno and Antonelli, 2018). Job allocation among workers and/or technology have often been approached through mathematical modelling (e.g., Fiasché et al., 2016). A task-based framework to choose between labour and capital has been presented by Autor (2013), who built a cost function to evaluate the competitive advantage of assigning a task to a worker or to a machine. Other similar approaches have been developed in a socio-economic perspective to study how the introduction of technology might modify the employment rate and the workers' wages in the future (Acemoglu and Restrepo, 2018).

   Despite great attention has been paid to estimate how the human tasks could and would be replaced by technology, literature lacks contributions which aim at studying at the operational level how the current jobs (and tasks) are affected by Industry 4.0 technologies in order to evolve the current job profiles. In particular, the task approach has not been merged with the opportunities offered by technologies, which will assist and augment human capabilities, redesigning their work activities.

Ras et al. (2017) state that one of the challenges related to the workforce in Industry 4.0 is to understand how human tasks will change in order to *"revise existing job profiles, build development and appraisal procedures for the existing workforce, and predict which new skills need to be developed in addition to be future proof"*.

According to these considerations, therefore, a more deep investigation is required to find a methodology to evaluate how the tasks of the workers in the Industry 4.0 context change in relation to the introduction of technology, able to offer a useful tool for academics and practitioners to analyse the current jobs and pave the way to the design of future ones.

2. **New competences and job profiles for smart manufacturing systems**

Strictly connected to the previous gap, a second relevant topic concerns the new competences for Industry 4.0. The literature background has highlighted how technology will transform traditional manufacturing processes into fully connected and real-time communicating ones, requiring more collaborative business and operating models (Schoenthaler et al., n.d.). According to this vision, in a smart factory environment workers will be expected to adopt new operational and management strategies. The previously outlined task-based approach is useful to identify the novel activities that workers are required to perform and it is the first step to identify how the nature of work will be changed and consequently how job profiles will evolve. Competences and skills are related to job profiles as well.

Several researches support the idea that, to interact and exploit the potentials of Industry 4.0 technologies, the operators, both at the shop-floor level and at the middle-management level, will need to acquire new competences and skills (Bianco, 2018; Dregger et al., 2016; Hirsch-Kreinsen, 2016). Further, Benešová and Tupa (2017) state that the requirement for qualification and skills in the future will be higher than at present, imposing a deeper reflection about education and workers' learning strategies.

Currently, few competence models specific for Industry 4.0 have been presented in the literature. They will be discussed more in detail in section 5.1.1. Generally, competence models refer to collections of knowledge, skills, abilities, and other characteristics that are needed for effective performance in the jobs, job families or functional areas (Pinzone et al., 2017). For Industry 4.0, these models offer a set of relevant competences, which are sometimes linked to specific job profiles and are developed based on literature, industrial interviews and focus groups.

All the models presented in literature, however, provide static frameworks in which competences are mapped, while they do not provide a clear understanding of what is the dynamic relationship between the introduction of new technologies and the related competence development that is required.

For this reason, the implication of the technology adoption on the workers' competences requires further investigations, in order to evidence the evolution of competences that companies need to face in dealing with the Industry 4.0 transformation.

3. Human integration in smart manufacturing systems

In the light of the new tasks and competences that characterise the operators of the next generation manufacturing system, frameworks and architectures for the human-technology integration are required. As discussed previously, the frameworks and reference models presented in literature so far never considered the human factor as an active part of the smart manufacturing system that is able to contribute to the efficient functioning of the system, which is always delegated to the machine intelligence.

The topic of human-machine integration, in literature, has often been addressed focusing on the human-machine interaction, namely considering as a crucial element the development of proper physical devices (the so-called Human-Machine Interfaces, HMI), designed to regulate the communication between humans and machines, displaying the operation status of equipment and enabling control to satisfy the needs of the user (Lee and Lee, 2016). In the context of Industry 4.0, HMI become intelligent and context-sensitive. The physical devices can be digitalised offering new opportunities to improve their usability and functionality along with better user experience (Gorecky et al., 2014).

Although this approach has been successfully researched providing also useful and industry-ready solutions, the Industry 4.0 scenario proposes a smart factory view in which humans are required to cooperate in a network composed by many agents (i.e. other humans, machines, intelligent devices, etc.) to perform various combination of physical and cognitive tasks (Jones et al., 2018). This suggests that further investigations have to be conducted in a wider perspective.

In particular, as promoted by Brauner and Ziefle (2015), the human factors need to be integrated into the technology development cycle, transforming pure traditional technical systems into socio-technical systems. However, in literature this approach has not been adequately featured.

The socio-technical approach would allow identifying clearly what are the roles that humans play in a smart manufacturing systems, highlighting the relationships between humans and technology, in the light of a holistic organisational view. In support to this, the HTO model discussed above suggests to consider and analyse together the three main aspects of technology, humans and organisation, to provide specifications to academics and practitioners to design the human-centred manufacturing systems of the future.

3.2.Objective of the thesis and research questions

As discussed before, three gaps have been identified in literature about the definition of the impacts of Industry 4.0 implementation on the human work. To cover these gaps, this research aims at addressing the Industry 4.0 paradigm from a socio-technical perspective. In doing this, the HTO model has been used as the reference model to describe and analyse the impacts of Industry 4.0 paradigm on the human work.

The HTO model turned out to be particularly useful to describe some prominent aspects to cover the literature gaps. In particular, from the literature analysis, some research hypotheses have been formalised, needing more investigation. Figure 3.1 shows the research hypotheses linked to the interfaces of the HTO model while Figure 3.2 shows the link between the hypotheses and the previously identified gaps.

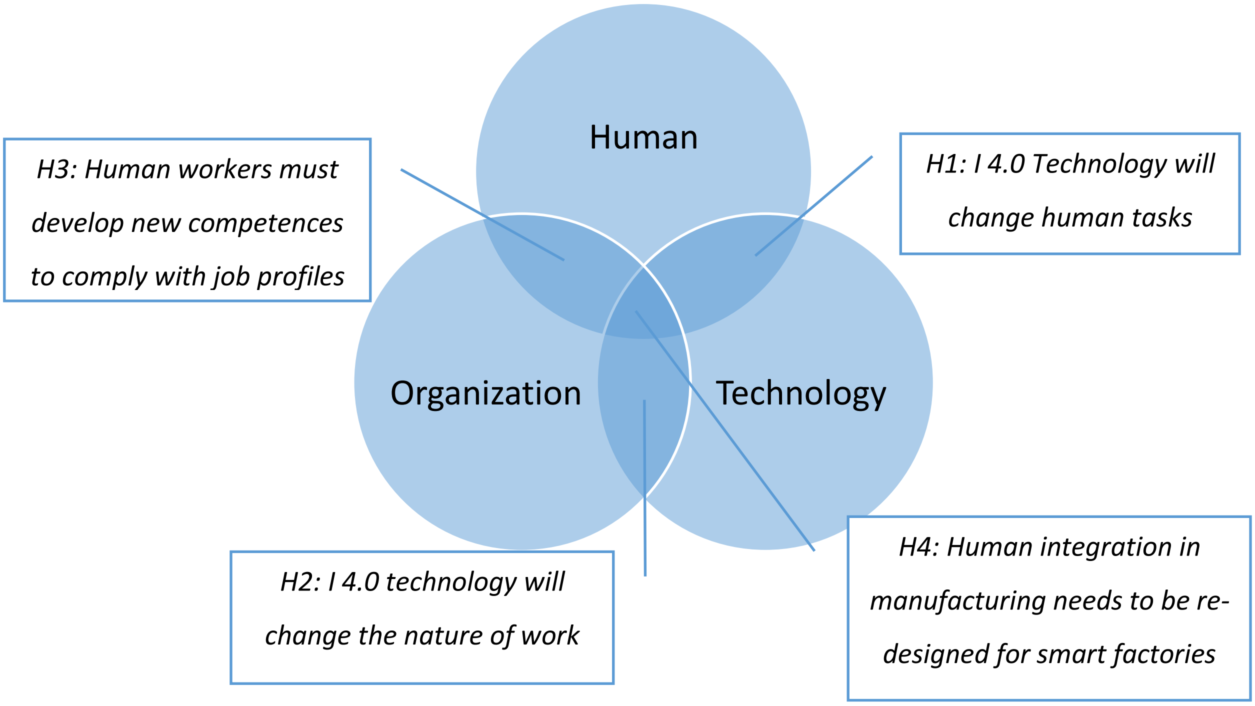

Figure 3.1 – Research hypotheses in the HTO model

The research hypotheses have been formulated in order to identify the contribution that this work could provide to the academic and industrial communities within the research stream of Industry 4.0. In fact, this thesis aims at both contributing to the body of knowledge from an academic point of view, as well as providing a more clear understanding about Industry 4.0 for practitioners and companies that are currently facing all the challenges related to the introduction of new technologies and operating paradigms.

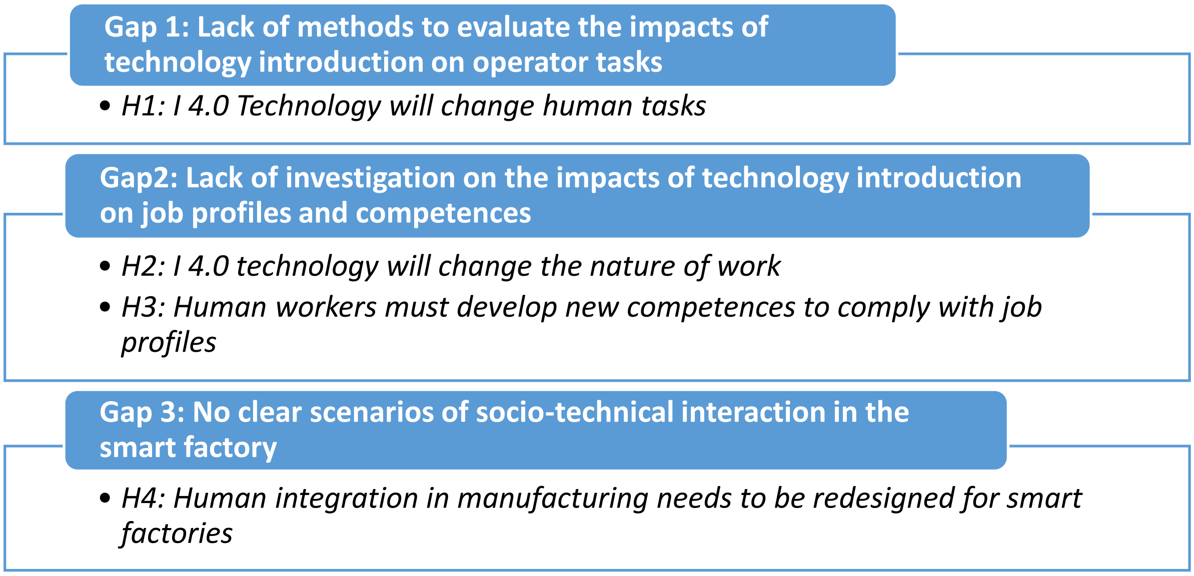

Figure 3.2 – Literature gaps and related research hypotheses

To fulfil the identified gaps and moving from the research hypotheses, three research questions have been defined.

- **RQ1. How do smart technologies affect the tasks of the operator in the context of Industry 4.0?**

This first research question aims at deeply investigating how the activities performed by human operators in the factories are affected by the introduction of new technologies. Actually, in recent literature, the concept of Operator 4.0 emerged to depict the combination of humans with Industry 4.0 technologies able to augment their capabilities (Romero, Stahre, et al., 2016). On the other hand, since many years, in the literature about work design and labour market, the task-approach has been presented to measure how computerisation and technology alter job profiles, skills and tasks (Autor et al., 2003). Contextual task analysis is recognised as the basis to design effective Operator 4.0 solutions, which significantly improve the abilities of human operators (Ruppert et al., 2018).

Merging these two aspects, namely reviewing the different kinds of interaction between Operator 4.0 and Industry 4.0 technology as well as using a task-approach, to answer this research question, a Task Classification Framework (TCF) and the related methodology to assess the impacts of technology introduction on the human work are proposed. This would fulfil the first gap.

- **RQ2. What are the competences required by introducing new work attributes that exploit Industry 4.0 technologies?**

In the light of the previously discussed changes that are expected in the activities performed by humans in the smart factories, it is reasonable to state that workers will need to develop new skills and competences (Pinzone et al., 2017). In particular, as the human-technology interaction will evolve and new operating models will be implemented to transform traditional production processes into fully integrated and digitalised ones, the features of traditional job profiles, also named work attributes (Das, 1999), will change, opening some challenges for the workforce. These challenges encompass the need for upgrading the technical knowledge of workers, along with the acquisition of new methodological and relational capabilities to manage the more complex smart factory processes. Proper understanding of the new required competences is crucial also to prepare the future workforce to fulfil the roles and profiles in the Industry 4.0 (Janis, 2018).

The research question two aims at shedding the light on these two main aspects: what are the work attributes affected by the introduction of Industry 4.0 technologies and how the workers' competences should mature to be aligned with the new requirements. At the same time, the relationship between the introduction of new technologies and the competence development will be explored. In addressing this question, different aspects of the job characterisation will be considered and also several categories of competences will be discussed, with the objectives of covering the second gap.

- **RQ3. How does a human-centred perspective affect the integration of Industry 4.0 technologies and humans into next generation production systems?**

Grounding on the previous research questions, this thesis finally aims at re-depicting the human-technology integration in the Industry 4.0 context. Despite the great importance of technology in the next future, it is fairly shared that humans will continue to play a predominant role, although it will be subject to changes in order to improve the performance of manufacturing systems. Defining workplaces in which the human dimension is the cornerstone is essential (May et al., 2015).

Research question three investigates how the introduction of new technologies affects the role of humans in the cyber-physical production processes that characterise the smart factory and what are the collaboration mechanisms between operators and machines. In particular, the production control and the decision-making processes of the factory are the focus of this analysis. The final goal of this research question is to provide a reference architecture to design in a human-centred perspective the manufacturing systems of the future, thus covering the third gap.

3.3.Research workflow

The aim of research is the creation and development of knowledge and the expected outcome is the contribution to knowledge. This thesis falls within the scope of Operations Management, which studies the processes and activities that produce goods and services in manufacturing, both from an operational and management point of view. One of the challenges in the field of Operations Management is usually the need to develop researches which create contribution and value for both academia and practice (Karlsson, 2008). Actually, the involvement in practice can range from the usage of data from real industrial companies to the implementation and validation of proposed research outcomes in a manufacturing context. In line with what has been discussed so far, this thesis aims at contributing to both the academic and industrial communities.

To do this, a research flow has been depicted and it is represented in Figure 3.3.

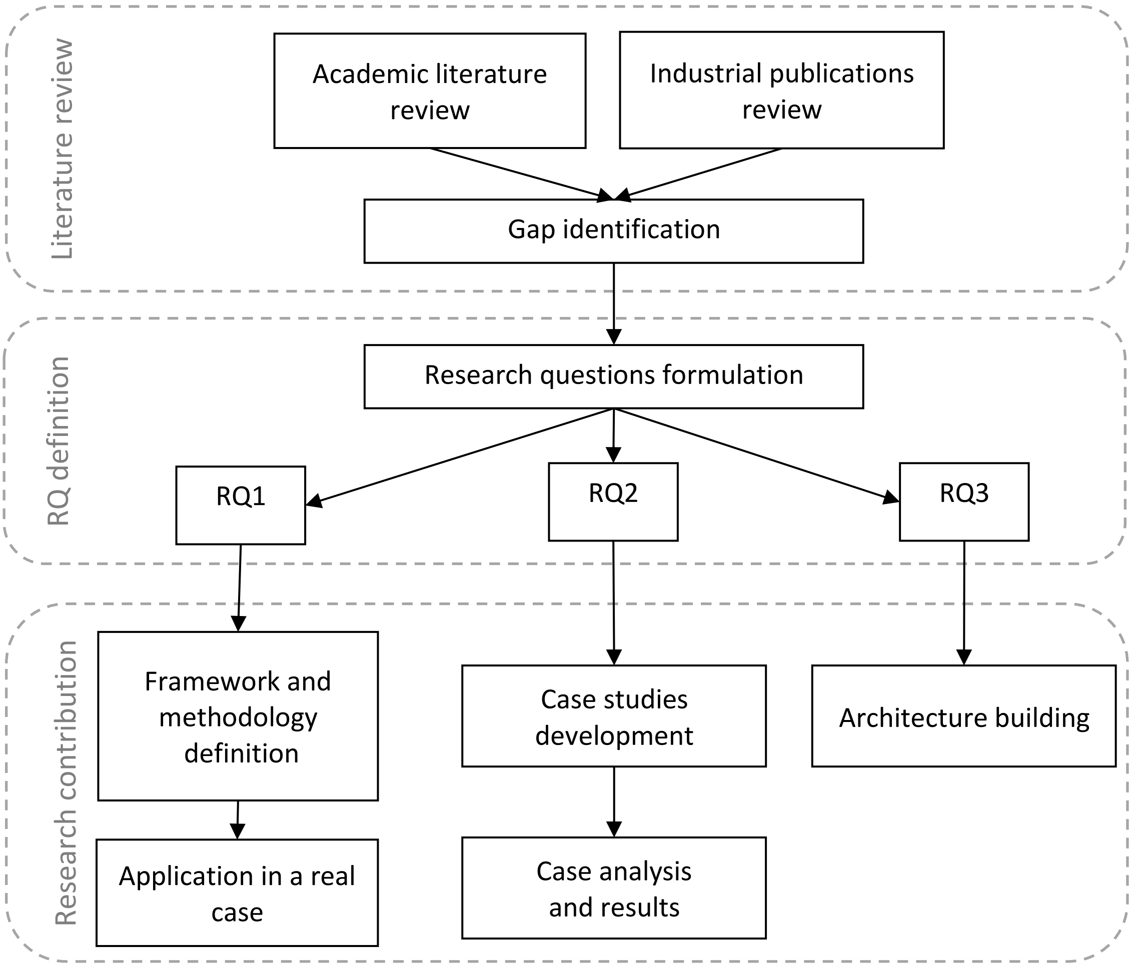

Figure 3.3 – Research workflow

Three main phases constitute the research flow:

1. **Literature review.** The analysis of the academic and industrial literature has been conducted as the first step of this research, to explore existing works in the field of Industry 4.0. The

literature phase represents a crucial element in the research flow because it creates the foundation for advancing knowledge (Webster and Watson, 2002). The scientific literature has been searched using the most relevant online databases, such as Scopus, Web of Science, Google Scholar, IEEE Xplore, JSTOR, and Science Direct. Also, other relevant contributions, such as reports and white papers from industrial companies, associations and consultancy groups, have been scanned. From the literature analysis, the three above-mentioned gaps emerged.

2. **RQ definition.** The second phase of the research workflow concerns the formulation of the research questions useful to cover the identified gaps and provide a contribution to academia and practice. Three RQ have been defined.
3. **Research contribution.** In order to answer the research questions, different research methods have been used. They are discussed in Section 3.4.

   RQ1 involved a first phase of theoretical development of a Task Classification Framework and the methodology to adopt it to evaluate the changes in the human work and a second phase of implementation carried out in a real industrial case, where the methodology has been applied. These contributions are described in Section 4.

   To answer RQ2, case studies have been conducted to explore the industrial perspective and needs in terms of new skills and competences of the workers as well as to envision how the work attributes have been impacted by the introduction of new technologies. The results from the case studies results provided the insights to build some propositions. This case research is discussed in Section 5.

   Finally, to answer RQ 3, a theory-building research has been developed, which is described in Section 6.

3.4.Research methodologies

As discussed before, the three research questions have been addressed using different research methodologies. In the following, the three research approaches are briefly explained in relation to the purpose of this thesis. The research is based on both deductive and inductive reasoning. In the first case, looking at the behaviour of real systems, the underlying causes and relations are identified and generalisations are formalised. In the latter, inductive reasoning starts by looking at the internal elements of a system and their relationships to understand the impact of changes in the properties of elements on the behaviour of a whole system (Dekkers, 2017).

3.4.1. Action research

Since the first seminal works in the field of socio-technical systems theory, action research emerged as a suitable methodology to lead advancement in theory as well as producing positive and practical social change (Pasmore, 2006). Action research can be defined according to four main characteristics (Coughlan and Coghlan, 2002):

- Research *in* action, rather than research *about* action
- Participative
- Concurrent with action
- A sequence of events and an approach to problem-solving.

The action research approach requires researchers to directly work in a real organisational system, from which it is possible to gather data, with the two objectives of solving a practical problem and contributing to science. Action researchers need to collaborate and be members of a group, community or organisation and need to take part in the changing or improving actions on a system, in order to learn from it (Coghlan and Brannick, 2005).

In this study, action research approach has been used mainly to develop the answer to RQ1. Indeed, the author spent about three years joining the day-to-day business activities and organisational processes of Brembo, a large Italian manufacturing company, which is currently involved in the business transformation toward Industry 4.0. Given the nature of action research, the investigation carried out in Brembo involved the two main goals of i) supporting the company in its specific process transformation towards smart manufacturing and ii) contributing to knowledge, by understanding how to measure the impacts of Industry 4.0 technologies on human work. The author contributed to the development of some Industry 4.0-based tools supporting the operations management of the company. This allowed a longitudinal process of observation and analysis which has been fundamental for the research development. In addition to the directly observable behaviours of the company workers, data collection has been also possible through specific focus groups and interviews with Brembo employees.

The involvement of the researcher in a real industrial context allowed the identification of both the technical and social implications and challenges in the introduction of Industry 4.0 technology, enabling the assessment and refinement of the proposed framework and methodology. Despite action research presents the risk of analysing a problem in a too situation-specific and contextual-dependent way, it can also lead to results which can be generalised and transferred to other situations (Checkland and Holwell, 1998).

3.4.2. Case studies / Interviews

Given the nature of this research, for answering to RQ2, an empirical approach with multiple case studies (Sousa and Voss, 2001) has been adopted. A case study is defined *'an empirical inquiry that investigates a contemporary phenomenon within its real-life context, when the boundaries between the phenomenon and the context are not clearly evident, and in which multiple sources of evidence are used'* (Yin, 2009). Thus, the case-study approach allows for observing companies' actual practices related to specific topics (Meredith, 1998; Voss et al., 2002) and allows for answering the questions 'why', 'what' and 'how' with a relatively full understanding of the complete phenomenon's nature and complexity. A case study is recommended when dealing with complex adaptive systems, such as digitalisation of companies' processes. In these cases, researchers should consider 'insider' and 'participatory' approaches to research (Ottosson and Björk, 2004) to capture depth, nuance and complex data during interviews (Mason, 2002). Within a case study, the researcher assesses the conditions surrounding the phenomenon to build a plausible explanation or to discover a causal relationship that links antecedents to results (Benbasat et al., 1987; McCutcheon and Meredith, 1993). Finally, field-based research methods, like case studies, are especially suitable for coping with the growing frequency and magnitude of changes in technology and managerial methods (Lewis, 1998), as is the case with Industry 4.0 adoption.

Case studies have been used in a deductive reasoning approach to understanding from field the impacts of new technologies of job profiles and worker competences. The detailed description of the case selection and the interview protocols used in the two developed multiple case studies are discussed in Sections 5.2.2 and 5.3.2.

3.4.3. Conceptual modelling

Along with case studies and action research methodology, theory-building through conceptual models and frameworks approach have been applied in this work. A conceptual model is *"a set of concepts, with or without propositions, used to represent or describe an event, object, or process"* (Meredith, 1993). Researchers usually agree that the aim of a 'good' theory is to explain clearly how and why specific relationships lead to specific events (Wacker, 1998). Conceptual models encompass conceptual descriptions, taxonomies and typologies, as well as philosophical conceptualisation. In addition, conceptual frameworks aim at explaining, further than representing, a system and the relationships among its elements (Meredith, 1993).

To properly address RQ3, the research has been built on a deductive research approach in which, starting from a well-founded knowledge, a generalisation is established, in order to be tested afterwards (Hyde, 2000).

For this purpose, the research topics concerning human integration in manufacturing processes have been deeply explored. In particular the theoretical underpinnings at the basis of the research are the socio-technical systems theory, which concerns the joint researches about technology and human aspects, and the theoretical concepts of multi-agent and holonic manufacturing systems, which have been used to represent the dynamic behaviour of human-technology integration in the operational control mechanisms of a Cyber-Physical Production System.

After deeply analysing the relevant literature, RQ3 has been investigated and conceptualised in the form of a theoretical architecture for designing human-centred Cyber-Physical Production Systems, aiming at representing the role of humans in the new scenario of the smart factory.

A summary of the research hypotheses, RQs and validation methods are represented in Figure 3.4.

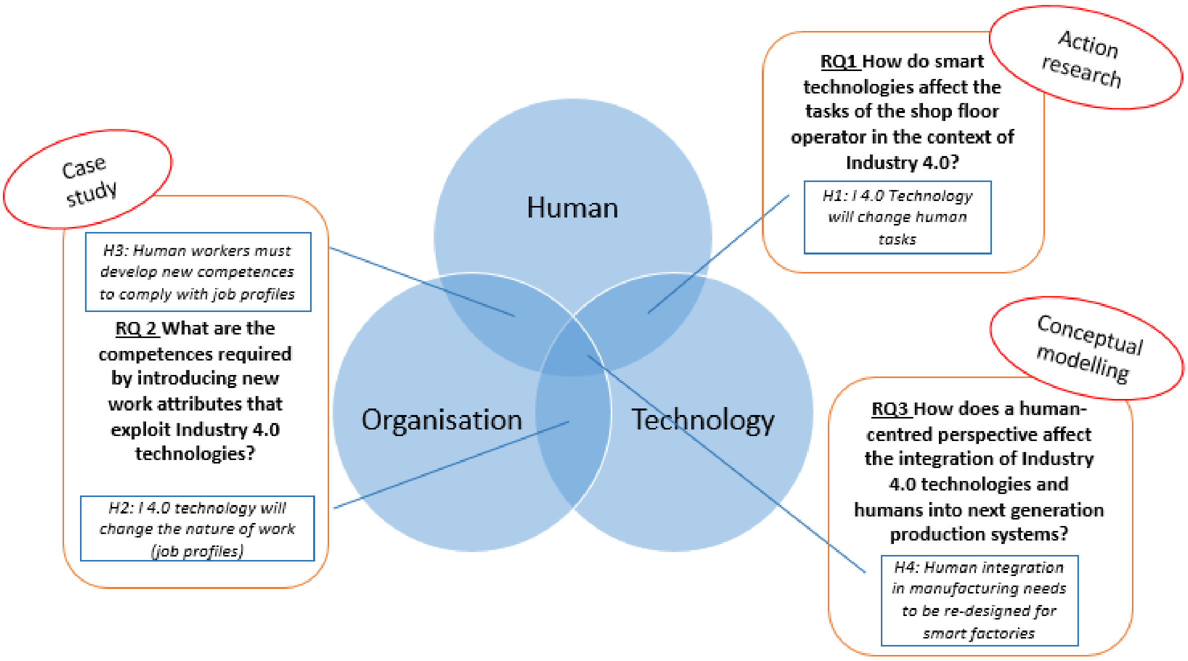

Figure 3.4 – Research objectives and workflow summary

4. THE OPERATOR 4.0: ASSESSING THE IMPACTS OF TECHNOLOGY INTRODUCTION THROUGH TASK ANALYSIS

According to the above-discussed research objectives, this chapter aims at investigating the impacts of the Industry 4.0 technologies introduction on the activities performed by operators in manufacturing processes. To analyse at micro-level how the work activities of humans will change in relation to the new technology introduction, the decomposition of human work into several tasks has been envisioned as useful to carry out the research. Indeed, a “task” is defined as “the unit of a work activity that produces an output”, and the task approach has been used successfully in the past to analyse the interactions between human capabilities and technology capabilities, as well as the task allocation between humans and machines (Autor, 2013).

The relevance of tasks characterisation in the work design has been postulated in the seminal work of Hackman and Oldham (1976), who identified as core job dimensions the *Task Identity* and *Task Significance*, which directly affect the motivation of workers and consequently the work outcomes. Further improving this model, Kiggundu (1981) introduced the concept of *Task Interdependence*, as a measure of necessary interaction and correlation between different activities and workers. The same concept was studied also by the Socio-Technical System theorists (Trist and Bamforth, 1951) and used to test the impacts of team work on the workers outcome (Vegt et al., 1998). Moreover, the Activity Theory was introduced in the 1980s with the goal of analysing the human actions in socio-technical systems (Engestrom, 1987).

Along with these foundational works, extensive literature in the labour studies has addressed the evolution of tasks that makes up jobs as a function of technological advancement (Cordery and Parker, 2012), suggesting that the task analysis represents an essential step to understand the changing working paradigms related to technological innovations that affect the industrial world.

Grounding on all these researches, to answer RQ1, first, a simple classification of human tasks is presented. Second, the thesis aims at providing a clear understanding of how technology can support human capabilities, proposing a methodology to assess the modification in the tasks’ set of operators in a smart factory. In doing so, the Industry 4.0 technologies are classified based on the augmentation and assistance they can give to operators in the manufacturing processes.

Finally, the chapter offers the application of the proposed methodology in a real industrial case, the manufacturing company Brembo, and a discussion about the impacts of the evolution of tasks on the upskilling and deskilling of workers

4.1.Human-technology interaction/collaboration: from the Operator 1.0 to the Operator 4.0

Despite the great importance given to technology in the Industry 4.0 paradigm, it is widely recognised that human cannot be fully replaced by machines/robots. However, the seamless integration of technological capabilities with human factors is one of the major issues in dealing with the process transformation required to give birth to smart factories (Kong et al., 2018). First of all, automated equipment and computer applications are sharing the work environment with humans (Mital and Pennathur, 2004). In addition, current trends and implementation examples indicate profound changes regarding human work tasks on the shop floor (Stern and Becker, 2017). Answering to the question “How human work will change?” is producing different perspectives, between those who stress the risk of replacing humans with technology and those who optimistically expect that human work will be re-evaluated and improved (Dregger et al., 2018).

Three main possibilities open up to depict the future human-technology relationships: automation, assistance and augmentation. In the first case technology will replace humans, removing the need of human effort; in the second case, automated software applications can assist humans through intelligent systems; in the third case, technology enhances human core capabilities providing specific contextual support (Assistance, Augmentation, and Automation | Platform Strategy – by Sangeet Paul Choudary). These three approaches will inevitably co-exist and will be strictly dependent on different technological implementations.

In literature, to represent the new role of humans in the Industry 4.0 paradigm, the concept of Operator 4.0 has been introduced, as the arrival point of an evolutionary path of human-technology interaction, which is represented in Figure 4.1.

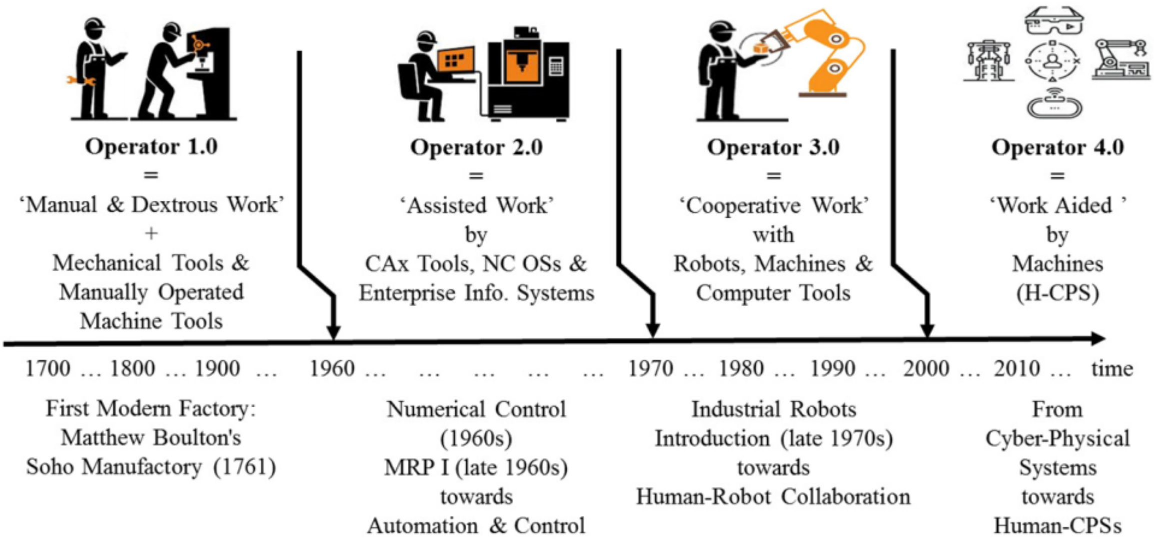

Figure 4.1 – Operators generation evolution (Romero, Bernus, et al., 2016)

If the work of Operator 1.0 had a predominant physical component, over the years the technological evolution has first provided software tools to program and control the machines, and then it contributed to making the production scenario increasingly marked by the collaboration between man and machines. Following this evolution, nowadays the Operator 4.0 can benefit from highly advanced production systems, able to optimize and self-regulate, as well as communicate in real time its operating status to the entire factory and beyond, exploiting the potential of the Industrial Internet.

In their works, further, Romero, Stahre, et al. (2016) envisions eight new typologies of Operator 4.0, whose capabilities are enhanced from different technologies each time:

1. The Analytical operator has the ability to manage the large amount of data collected by sensors or intelligent machines during the production process and analyse these complex data sets to obtain KPI for process control and predictions;
2. The Augmented operator exploits augmented reality technologies to improve the information exchange with the environment, using digital devices such as tablets, screens, glasses in order to assimilate more information than a standard operator;
3. Collaborative operator cooperates with robots in carrying out work activities (e.g. with cobots) with the aim of performing repetitive work with an improved ergonomics;
4. Healthy operator wears devices designed to measure stress, heart rate and other personal parameters, such as the position, which are able to detect his health status preventing risks and accidents;
5. Smarter operator has the ability to connect the information generated by an intelligent system applied to the machines with the knowledge and experience developed by each operator, generating solutions to problems that need a problem-solving approach based on experience;
6. Social operator uses interconnection services with intelligent resources, known as the Enterprise Social Networking Service, to share information at all levels and provide better decision support.
7. Super-strength operator wears light and flexible biomechanical exoskeletons that, for example, allow him to increase the strength to perform manual operations without any effort.
8. Virtual operator is immersed in a virtual reality where he can perform simulations of design, production and assembly using a computer, to increase his process awareness and perform better decision-making, avoiding the complexity and risks of the real system.

By the above-presented typologies, it is possible to argue that different kinds of interaction between humans and technologies are available, according to the features of the tasks that have to be performed. Indeed, the Operator 4.0 typologies embed all the possibilities of automation, assistance and augmentation provided by Industry 4.0 technologies, and, in real manufacturing systems, it is possible to combine more typologies in a single operator.

In literature, then, it is widely recognised that one of the major implications of Industry 4.0 concerns the modification of the human work, both due to the possibility to automate and replace some tasks and the requirement of enlarging the variety of tasks performed by humans in the light of the technological support provided to operators. Especially in countries where the labour cost is high, in fact, manufacturing companies are encouraged to replace the human workers with robots. Nevertheless, it may also happen that automation is not dictated by the need to reduce labour costs; this is the case of Industry 4.0, in which the new technologies can be combined to human capabilities to gain the best trade-off between productivity and flexibility. According to Becker and Stern (2016), future workers will be distinguished by their cognitive and abstract abilities as the monotonous and standard works will be replaced by automation, which still does not have the possibility to self-organize.

In the following sections, a framework to classify human tasks and assess how Industry 4.0 technologies will impact on them will be presented.

4.2.The Task Classification Framework (TCF)

In the previous discussion, it has been stated that technologies will support operators, ensuring that, in many cases, humans will be required to change their way they usually do work activity. The adoption of new technology can both create new activities and delete some others that become redundant and therefore no longer useful. To understand how the operator's job actually changes, it could be useful to classify the main types of tasks that the operators must perform, in order to align these tasks with the technological capabilities that can support them and finally assess how the tasks can be modified. Identifying a changing task means to compare how the task assigned to the operator was carried out before the introduction of the technology and how it is performed afterwards, assuming that if a task is performed in the same way before and after technology introduction, the technology has not a considerable impact on the operator work. Thanks to this classification and comparison, it will be possible to analyse which types of tasks are those most likely to undergo a change due to the support of a technology during a work activity.

In the literature, there are many types of tasks that vary according to the different characteristics. In the following, the most relevant and discussed tasks’ characteristics will be presented, according to the purpose of this study.

4.2.1. Routine vs. Non-routine

The first classification is between routine tasks and non-routine tasks.

In the case of a routine task, we mean an activity that is performed following programmed rules. The methodical repetition of certain types of work makes it possible to create standard and well-understood procedures without substantial changes over the long term (Autor et al., 2003). According to Autor and Price (2013), routine tasks are job activities that are sufficiently well defined that they can be carried out successfully by either a computer executing a program or, alternatively, by a comparatively less-educated worker who carries out the task with minimal discretion. In manufacturing, typical routine tasks are repetitive production activities, such as loading/unloading or simple assembly tasks. The repetitiveness of routine tasks is considered as a relevant parameter to determine the degree of substitutability and complementarity of the man with the machine. Tasks that are codable, namely activities that can be translated into simple operations, logically ordered in order to guarantee the quality of the output, can be carried out by a machine or a computer successfully as well.

Conversely, non-routine tasks are not characterised by well-defined procedures and therefore are difficult to be performed by a standard computer or machine. Non-routine tasks are abstract tasks, like those ones related to managerial, technical and creative occupations, which require problem-solving skills, intuition and analytical capabilities, but also situational adaptability or visual and language recognition.

The main reason why it is not possible to define a procedure is that non-routine activities require skills that currently can not be transformed into programmable rules and actions (Autor et al., 2003). For this reason, non-routine tasks fall into the non-codable category as they imply the recognition of complex models as well as the coordination of thought and action.

4.2.1. Cognitive vs. Manual

The second classification dimension concerns cognitive tasks and manual tasks.

The difference between the two, in this case, is more intuitive: manual tasks are physical activities that can be defined in terms of a set of movements and require the sensorial abilities (Levy and Murnane, 2005), while cognitive tasks, on the other hand, concern mental activities (Cortes et al., 2017).

The combination of routine, non-routine, cognitive and manual features generates a number of different task types. In particular, for non-routine cognitive tasks, some authors further distinguish between non-routine analytical tasks, such as solving problems that arise in a non-continuous way and therefore require a different approach every time, and non-routine interpersonal tasks, such as the ability to negotiate with customers or manage other employees and operators.

Table 4.1 shows some example of manufacturing tasks classified according to the above-discussed characteristics.

	Routine	Non-routine
Manual	- Manual assembly - Loading/Unloading - Picking	- Maintenance reparations - Forklift driving - Setup operations
Cognitive	- Data collection - Calculation - Accounting	- Planning - Data analysis - Resource coordination

Table 4.1 – Routine/Non-routine and Manual/Cognitive tasks examples

Analysing the EU labour market, Autor and Price, in 2013, namely just after the launch of Industry 4.0 initiatives, provided a picture of the worker tasks, highlighting that in the last decades the demand for cognitive and non-routine tasks is increasing, while routine activities are decreasing significantly (Figure 4.2).

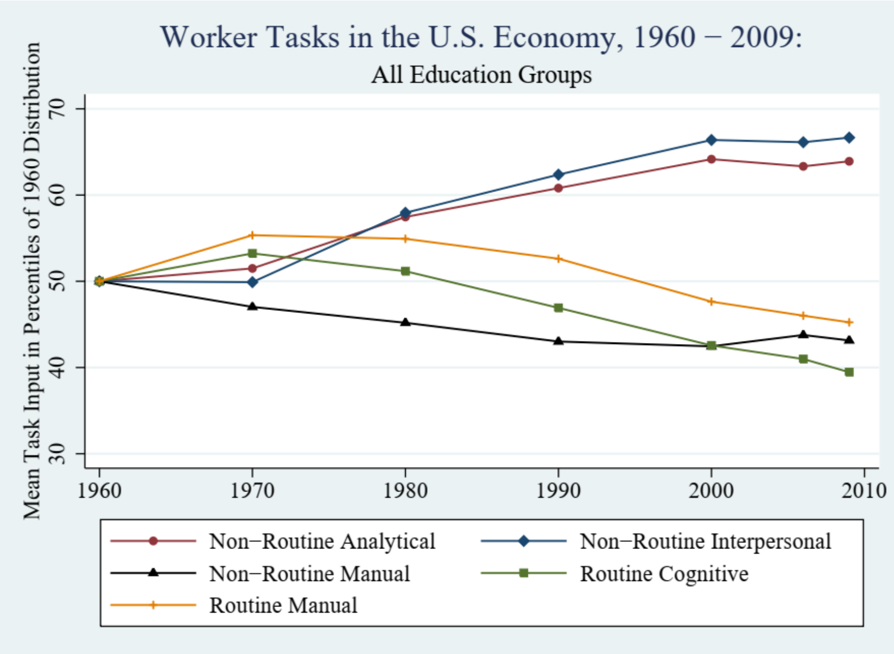

Figure 4.2 – Worker tasks in US Economy (1960-2009) (Autor and Price, 2013)

4.2.2. Social vs. Individual

In addition to the above-mentioned features, another relevant aspect of the tasks performed by humans is the level of social interaction involved. Some studies suggested that operators who have a low level of social interaction in their tasks are more subject to computerization because even simplified versions of typical social tasks prove difficult for computers (Frey and Osborne, 2013). Zero or minimum level of social interaction, in fact, mainly regards tasks that are strongly formalised and standardised and can be conducted independently by a single operator. Augmenting the need of communicating with others, the tasks involve increasingly mediation activities, which are difficult to replace by technology. At the highest level of social interaction strong social cohesion and team working are required (Fantini et al., 2018).

According to these three dimensions (i.e. routine/non-routine; cognitive/manual; social/individual), a Task Classification Framework is represented in Figure 4.3, aiming at providing a general model in which tasks can be mapped and a comparison between human work activities before and after the Industry 4.0 technology introduction can be easily performed.

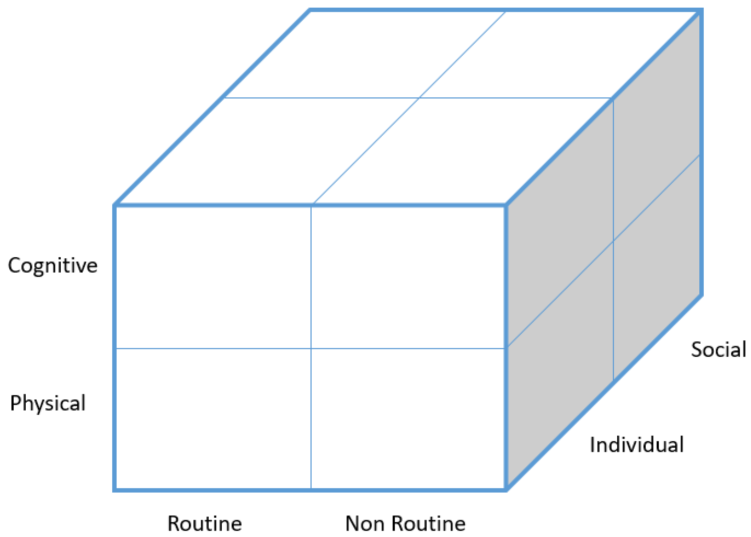

Figure 4.3 – Task Classification Framework

4.3.Description of the methodological steps

Exploiting the TCF, in this section, a methodology to assess how human work is modified by the introduction of new technologies is presented. The methodology aims at identifying how the specific work activities referring to a job profile will change in relation to the adoption of new technologies and related tools. In particular, the methodology allows to map and compare the AS-IS and TO-BE tasks' set of a job profile, highlighting different possible scenarios: i) some tasks will disappear, replaced by new tools and technologies; ii) some new tasks will emerge and can be created to manage and exploit the potentials of technology; ii) some tasks will be transformed or can move from a quadrant to the other in the TCF, showing how technology can change the work content and procedures of a task.

Beyond offering a theoretical contribution, this methodology also addresses engineers, human resources managers, factory designers and all the industrial stakeholders which are responsible for designing the job profiles, and it aims at providing a useful tool for deeply understanding how some jobs need to be re-designed in terms of task allocation after the Industry technology introduction.

Hereafter, the four steps of the methodology are explained.

4.3.1. Identification of traditional tasks

Designing a job implies to define all the tasks that must be carried out to get a work outcome, which can be a tangible or intangible product. As a first step, an evaluation of the current activities carried out by a specific operator is required. At theoretical level, the tasks pertaining to a job profile are defined in the job description and, at practical level, are applied within the activities that are carried out daily by workers. In this first step, the tasks of a job profile need to be first identified and then classified according to the TCF. To do so, the job description is considered, but it is also possible to apply in-field methods to collect this information. Effective job analysis methods generally allow examining how workers spend their working time, namely what are the tasks they perform and the time required to perform them (Robinson, 2009). Several approaches are presented in literature to collect these data, such as the self-reporting or the work sampling techniques.

Once the set of tasks performed by a worker in a specific job role has been identified, the tasks can be analysed and classified according to the three dimensions of the TCF, to formalise if they are repeated frequently or they are non-routine activities, if their content is manual or cognitive, and if they involve a social interaction or not.

As a result, the classification can be also graphically depicted in the TCF, providing a mapping of the AS-IS tasks' set (see the example in Figure 4.4).

4.3.2. Smart Technologies classification

The Industry 4.0 technologies, which have also been referred as smart technologies and have been discussed in Section 2.2.1, can have different fields of implementation and consequently can impact in different manners on the human work in the manufacturing system. In particular, technologies can support humans enhancing their capabilities both at the physical and cognitive level (Jones et al., 2018). In the first case, the introduction of technologies such as collaborative robots or exoskeletons aims at combining the efficiency of automation systems with intrinsic flexibility of manual operations (Romero, Stahre, et al., 2016). In the latter, technology enables better performance in cognitive capabilities, which are defined as the capacities of undertaking mental tasks (e.g., perception, memory, decision, etc.) (Romero, Bernus, et al., 2016).

In Romero, Bernus, et al. (2016), further, three different kinds of support given to operators by technologies have been defined as physical, cognitive and sensorial aids. The physical aid to operators provided by technology concerns undertaking physical tasks needed for the transformation of an asset or for the provision of a service, by a joint effort of technology and humans. Different kinds of interactions can occur through several attributes, such as strength intensity, speed of physical work performance, accuracy and many other attributes. Also, the simple walk that is useful for work purposes is considered an ability of the operator to perform a physical job. Technology supporting physical activities performed by operators can improve productivity reducing excessive or prolonged human effort, which can generate risks for his health and for the quality of the work done.

The second aid provided to operators is the sensory one. In this case, technology can support and improve the human ability of data acquisition from the surrounding environment, which represent a crucial activity to perform decision-making processes. All operators have the ability to collect visual, olfactory, sound and other types of data, but, in addition, the most important human capacity is to select data related to the work they are doing. Within the same environment, two different operators who perform the same job would collect almost the same data but the processing and logical choice of which to analyse could lead to different decisions. Technology is able to overcome also human sensorial deficit, normalising and amplifying signals. Moreover, smart sensors, embedded with artificial intelligence, can be able to filter the necessary information by discarding all those not useful for the task.

Finally, a third type of aid described by Romero, Bernus, et al. (2016) is related to the cognitive ability of an operator, that involves reasoning, memory, perception and decision that are necessary for the job and for certain operational settings, since cognitive tasks are used to guide and decide. Some new technologies can help operators to perform mental tasks, producing an improved quality of the performed tasks and reducing the stress and workload associated with the process of reasoning.

As a second step of this methodology, then, an analysis of the new technologies that are introduced in the analysed manufacturing systems and whose capabilities support a specific job profile is required. In particular, the technologies shall be mapped with the same features of the task. Referring to the technologies listed in Table 2.2, it could be useful to classify them in relation to the physical or cognitive support provided to the operators in manufacturing Table 4.2.

Despite specific support to sensorial abilities of human has been before described apart, this aid is strictly related to the physical sphere. For this reason, in this study, it will be considered as a physical aid as well.

The provided classification is based on the literature review. Totally, 64 articles have been considered, published from 2013 and 2019. They can be divided into two groups, according to their content. The

33 contributions that belong to the first group of papers directly report the application of a specific technology in a defined context, allowing the evaluation of the role that technology has in supporting the activities performed by humans. For instance, some articles provide a description of pilot cases in selected enterprises or depict the implementation of technological applications developed by the authors. In this group, two or three papers specifically address each technology (one of these papers is reported as an example in the columns “Source” of Table 4.2). The second group of papers, which is composed of the remaining 31 contributions, includes literature reviews about Industry 4.0 technologies and conceptual models and architectures for the implementation of technologies. Some of these contributions, in particular, describe from a theoretical perspective the interaction of humans with several technologies. For this reason, also if they do not report specific technological applications, they have been taken into account to abstract the impact that technologies have on human activities and build the proposed classification.

From the classification, it clearly appears that the majority of technologies supports the cognitive tasks usually performed by the workforce. Therefore, also according to the previous discussion about technology adoption in manufacturing companies, it is possible to argue that main expected benefits of Industry 4.0 implementation concern the opportunity of improving typical human intelligence processes and operations, providing large amounts of data, information, and additional calculating capacity. In fact, the limitations of human work often depend on the restricted capacity in dealing with complex and multiple systems (Pacaux-Lemoine et al., 2018).

For this purpose, cognitive technologies provide efficient assistance to raise situation awareness in operators and upgrade manufacturing processes management by workers. IoT, big data analytics, cloud technologies, as well as horizontal and vertical integration, contribute to the development of new smart manufacturing processes in which humans and technology complement each other to achieve common goals of productivity, flexibility and responsiveness, which are current market requirements and demands (Lee et al., 2014).

Concerning the other two dimensions of the TCF, it is not possible to provide a univocal classification for each technology. According to the frequency of tasks performing, the same technology can support both routine and non-routine activities; for instance, it is possible to use analytics both for recurring data reporting or KPI evaluation and for contingent specific problem-solving or prediction purposes. Also regarding the social interaction feature, Industry 4.0 technologies can support tasks that can be performed both individually or requiring social interaction. For instance, augmented reality tools can support both individual and in-team training activities.

According to the specific technology implementation, then, a more detailed classification of the technology in the three dimensions can be done.

Physical support			Cognitive support		
Technology	**Capability**	**Source**	**Technology**	**Capability**	**Source**
Augmented reality	Sensing	(Syberfeldt et al., 2016)	Cyber-Physical Systems	Decision making	(Lee, Ardakani, et al., 2015)
Virtual reality	Manual operations	(Cecil and Jones, 2014)	Internet of Things	Data collection and communication	(Lee et al., 2018)
Advanced robotics	Manual assembly	(Boston Consulting Group, 2015)	Big data analytics	Data analysis	(Lee et al., 2013)
Additive manufacturing/ 3D printing	Manual operations	(Liu et al., 2017)	Cloud technologies	Planning and control	(Wang, 2013)
			Smart sensors	Data retrieval	(Boston Consulting Group, 2015)
			Simulation	Optimisation	(Hou, 2013)
			Additive manufacturing/ 3D printing	Design	(Brettel et al., 2016)
			Energy saving	Decision making	(Seow and Rahimifard, 2011)
			Horizontal and vertical integration	Planning, diagnostics	(Wang, Wan, Li, et al., 2016)
			Multi-agent technologies	Decision making, scheduling	(Gaham et al., 2015)

Table 4.2 – Classification of Industry 4.0 technologies in relation to the physical or cognitive support

4.3.3. Identification of changing tasks

After identifying the AS-IS tasks' set of the job profile and assessing the technological capabilities to support human activities, a TO-BE map of the tasks performed by the operator after technology adoption is required. In this third step, similarly to what occurred in the first one, the activities that are carried out by the human worker are mapped and classified according to the TCF. In this case, it is mainly useful to conduct an in-field investigation, because the job descriptions usually are updated sometime after the technology introduction. In fact, the changes that the technology adoption brings into the content and ways of working are often not defined *a priori*, and companies usually react to the changing work scenario offered by technology. Moreover, the aim of this methodology is precisely to support the evaluation of how human work changes and consequently how the job roles and description have to be aligned to the technological innovation introduction. However, a deep investigation of the new job profiles in the Industry 4.0 context will be the focus of Section 5.

In this methodology, this third step aims at providing a TCF filled with the new tasks' set in order to compare it with the previously produced (step 1). In particular, from the comparison of the two frameworks, it is possible to see how some technologies can replace tasks that usually are performed by humans, for instance, thanks to automated production processes or automatic intelligent algorithms able to perform the same activities in less time. On the other hand, the new technologies can trigger the creation of new tasks, for instance in relation to the new data and information flows that have to be managed and analysed by humans in order to catch value. Finally, it is possible also that some tasks can be transformed and performed with increased efficiency thanks to the use of technology. For example, this is the case of collaborative robots that help operators in performing precision manufacturing tasks (e.g., assembly), improving the efficiency of the operations in terms of time and also quality of the manufactured product.

The comparison between the AS-IS and TO-BE task classification frameworks can include also a quantitative analysis of the time spent on each task. In fact, over the whole time available to the operator to perform the tasks assigned to his job profile, it can be possible that the technology introduction brings changes in the time percentage employed for each activity. One of the issues while dealing with new technology adoption, indeed, is the re-organisation of the working time according to the changing tasks, which is the objective of the fourth and last step of this methodology.

4.3.4. Re-balancing of the task allocation after the introduction of technology

As a result of the previous step, a new set of tasks after the technology introduction has been identified highlighting the transformation from the AS-IS status to the TO-BE situation. This fourth phase, therefore, aims at supporting the re-arrangement of job profiles in terms of time balancing, according to the new tasks' set. In fact, in the light of the technology introduction, it could be possible that the time amounts allocated for the various activities carried out by the operator are modified. In particular, the tasks that are completely replaced by technology (e.g. automation) generate free time for the worker. Also augmenting or assisting technologies, able to improve the efficiency of task execution, create time savings. At the same time, conversely, new tasks need to be performed and require additional working time. Re-balancing the task allocation after the technology introduction, then, is a fundamental step to ensure an efficient and effective human work.

In this fourth step, then, the time gap between the AS-IS and TO-BE situations can be analysed in order to understand if a re-allocation of tasks among different workers or job profiles need to be performed.

As an example, we consider a simple application of the methodology to the job profile of an assembly operator. The methodology is depicted in Figure 4.4.

In the first step, we suppose that the operator employs 100% of his working time performing repetitive manual assembly activities. The operator usually performs the assembly individually, without social interaction. In this context, a collaborative robot (cobot) able to support the operator in the operations that are more difficult and time-consuming is introduced. This technology can be mapped supporting the individual physical task of the operator (step 2).

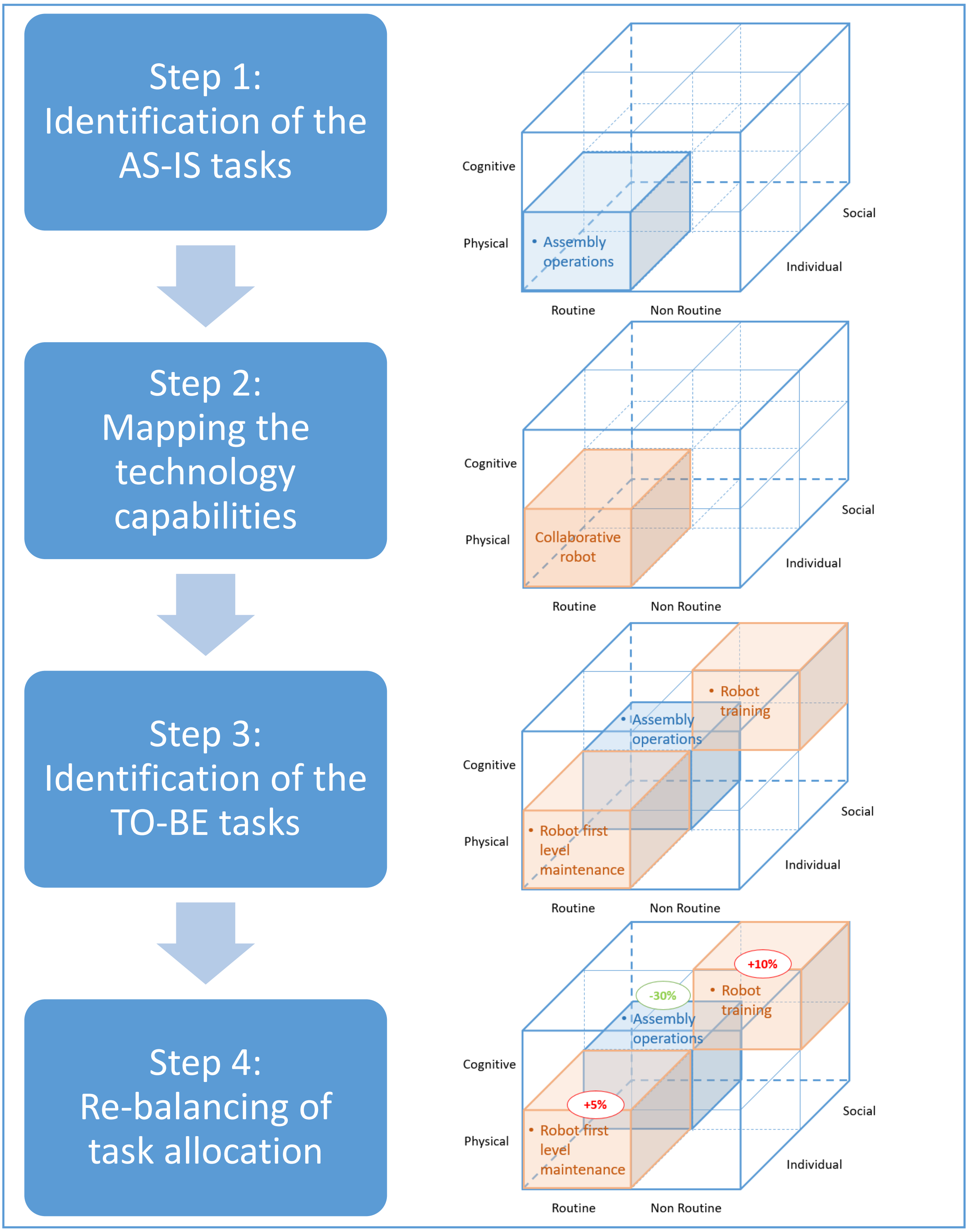

Figure 4.4 – Methodology example

After the introduction of the cobot, some changes in the work of the operator can emerge (step 3). In fact, the task concerning assembly operations is no more performed individually, but it is carried out in collaboration with the robot. The task, then, can be classified as a physical, routine and social task. At the same time, to enable the efficiency and the availability of the cobot, the operator is required to perform each day some first-level maintenance activities, representing physical, routine and individual tasks. Furthermore, the cobot needs to be trained at variable intervals, for instance, according to the need of supporting humans in the assembly of new kind of products, adding a new cognitive and social task. At the end of step 3, then, the operator in the TO-BE state is requested to perform three tasks rather than one. Finally, the analysis of the time related to the new tasks' set is performed. If the cobot is able to make more efficient the assembly, it is possible to quantify the time saving, which in this case is supposed to be the 30%. At the same time, over the whole working time of the operator, the new activities are supposed to employ the 5% (Robot first level maintenance) and the 10% (robot training) of the time. The time gap that emerges from the analysis is that finally the operator has a 15% of time which is free and not used to carry out production activities anymore.

Overstepping the above-discussed example, in the last step, the application of the methodology to a real production case may bring out three scenarios:

1. *The time required by the new tasks is equal to those required before technology introduction*. In this case, the working time of the operator does not change, but, if some new tasks appear or old tasks change in their content (i.e. move in the TCF), the workers may need to acquire new competences and skills.
2. *The time required by new tasks is more than those one required before technology introduction*. In this case, the work content pertaining to a single worker must be re-allocated to other job profiles. For instance, new job roles related to coordination and management activities can be required to perform mainly cognitive and social activities (see also Section 5).
3. *The time required by new tasks is less than those one required before technology introduction.* This scenario could be quite common if the technology introduction concerns advanced automation and robotics. In particular, this scenario can be related to the reduction of physical and routine tasks that are codable and simply replaceable by machines. In this case, re-balancing the task allocation in the workforce is essential to avoid the risk of reducing the human work, generating relevant job losses. It is worth noticing that if automation completely replaces some tasks, at the same time it is responsible for the creation of new complex tasks (Seghezzi, 2017), which in turns brings the creation of new job profiles. For this reason, in dealing with this third scenario, to avoid the unemployment of low-skilled workers, who

traditionally are in charge of manual and repetitive activities, it is necessary to invest the time that has been saved from the technology introduction to adopt different strategies of upskilling and reskilling of workers, through training and education. A more detailed discussion about this will be presented in Section 4.5.

4.4. Application of the methodology in a real case: Brembo S.p.A.

4.4.1. Industry 4.0 introduction in Brembo

The TCF and the related methodology aims at providing companies with a useful tool to analyse how the employees' tasks will change in relation to new technologies introduction. For this reason, in this section, the application of the methodology to a real industrial context is discussed.

To carry out this research, the author has been involved in a 3-year research project called "Smart Manufacturing 2020", founded by the Italian Technological Cluster Intelligent Factory, in collaboration with many partners from both industry and academia. In particular, the research activity concerned the introduction of new technologies and tools for the transformation of traditional manufacturing processes into smart manufacturing ones. The end-user of the research project was Brembo, a large manufacturing company located in the Bergamo province, which is a worldwide leader for the production of braking systems for cars and motorbikes. Inside the company, the investigation focused on the company's departments of machining and assembly for the Passenger Car Systems Business Unit, in the Italian factory, which has about 1,000 employees and produces in excess of 2,600,000 units per year. The factory has approximately 50 CNC machines and 50 assembly lines and, starting from 2014, is connecting this equipment via IoT to create a complex enterprise network and enable real-time communications within the factory.

During the first two years of the PhD course, the author regularly joined everyday business and manufacturing activities of Brembo and frequently took part in meetings in the company, supporting the strategic implementation of Industry 4.0 technologies to achieve a smart factory view. The involvement in the day-by-day activities of the company, and in particular within the Brembo Continuous Improvement department, which is in charge of the technological innovation introduction inside the factory, allowed the author to gain deep knowledge about the company, its dynamics and the challenges that practitioners have to face with new technology introduction.

In particular, among all the Industry 4.0 projects that Brembo is carrying on, the author has been involved in the activities related to the development of a web-based platform to monitor and analyse the data collected by the connected machines, in order to improve the process control and optimisation. According to an action research approach, during the time spent in the assembly and machining departments of the company, the author participated and contributed, since the first phases, to the concept and implementation of two main tools for the improvement of the manufacturing operations, which are called Analytics and Orchestrator.

Analytics is a web-based tool which allows the users to build and manage multidimensional databases and dashboards, useful to monitor, analyse and report the performance indicators of the manufacturing systems. To prepare the Analytics implementation, a previous consistent activity has been conducted by the IT team of Brembo to connect all the shop floor machines, in order to converge the data from large amount of hardware (such as PLCs, NCs, SCADAs) that are installed in different department of the factory. In particular, the deployment of customised drivers allowed a prompt data acquisition from machine supervisors and PLC/NC and the simultaneous match between machines data with the IT systems, in order to create aggregated data in a central Data Warehouse supporting Analytics tools. Indeed, Analytics is able to manage instantaneously data streams, which are shared via IoT by the machines, and match them with the data contained in the IT systems of the enterprise, such as the ERP and the MES, offering several opportunities to visualise and aggregate data to carry out complex analysis.

In the research project, the Analytics tool has been developed, based on the requirements of different areas of the factory, i.e. the quality department, the production department, the maintenance department, the process development department. Several focus groups and interviews have been conducted to collect the requirements from the users, in order to develop a tool really useful and able to support positively the work of the people. According to the suggestions of the managers of the abovementioned enterprise areas, the Analytics tool has been developed with the following functionalities:

- Live visualisation of the production plant, which includes the overview of the equipment status and the in-progress production orders (Figure 4.5);

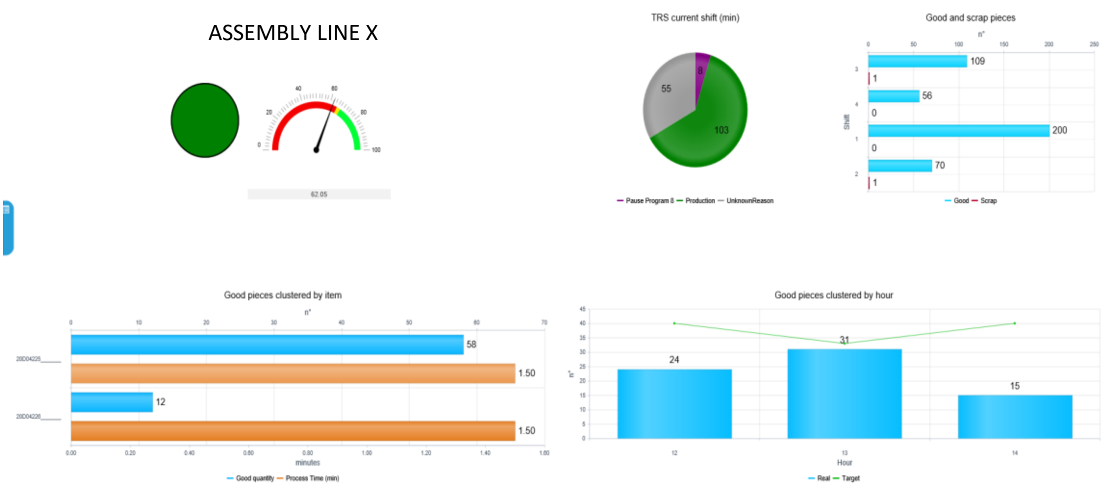

Figure 4.5 - Visualisation of the production progress of a single assembly line

- Instantaneous visualisation of performance indicators (such as the OEE) and workforce employed;
- Data analysis dashboards to investigate process parameters and scraps in order to support the process development, maintenance, continuous improvement, production and quality departments (Figure 4.6).

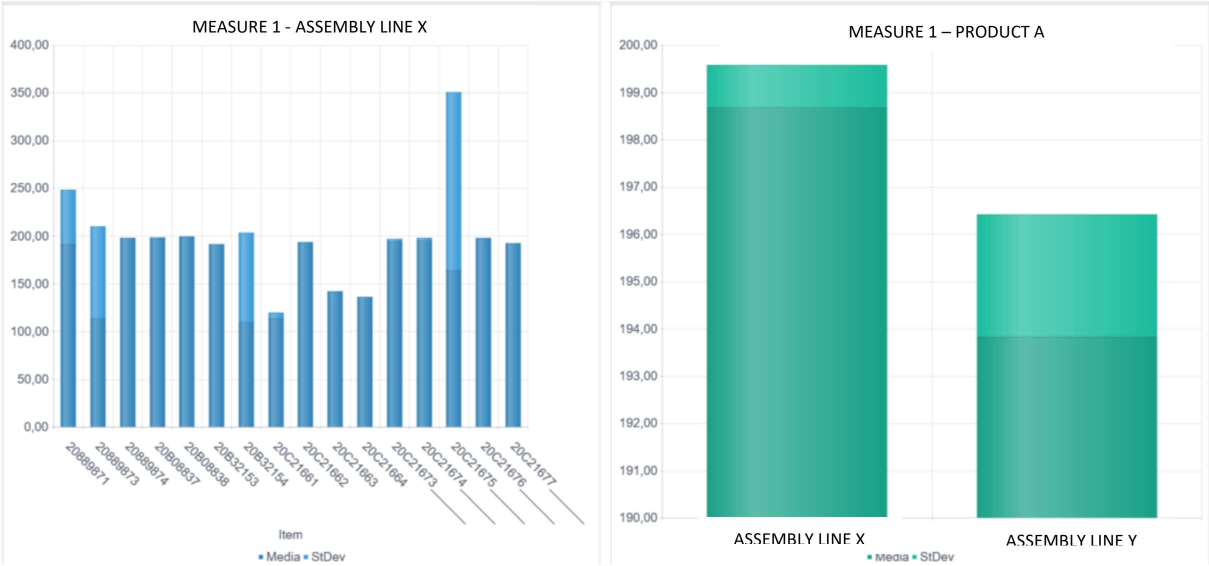

Figure 4.6 – Example of a dashboard for the analysis of process parameters

Orchestrator is a web-based software which allows the execution of a process in a structured way, through the digitalization of the information flow. Actually, it is a Business Process Management Component which allows to model and automatically execute processes in cross-platform and cross-role workflows. It is based on a process model with BPMN 2.0 standard (Figure 4.7) and a process execution which is managed according the assignment of tasks to the right stakeholders. In addition, relevant KPIs can be extracted by Orchestrator and analysed with Analytics.

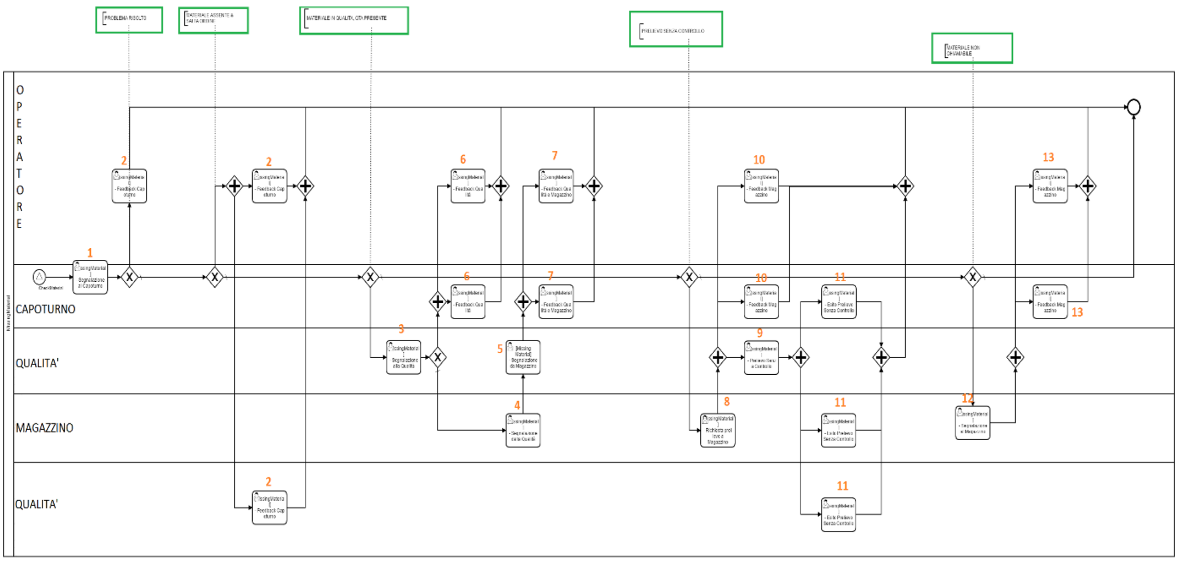

Figure 4.7 – Missing material call process modelled with BPMN

In Brembo, Orchestrator has been developed to optimise critical processes, in order to guide the activities implementation, to reduce the time to share the information, to monitor the execution of the tasks and to facilitate the alignment among departments.

In particular, two processes have been digitalised through Orchestrator:

- The material calls from the assembly lines operators;
- The detection of anomalies in the assembly lines process parameters.

For the two processes, Orchestrator also allows the tracking and analysis the execution of the tasks, thanks to the integration with Analytics.

In the following sections, the use of Analytics and Orchestrator will be better discussed in relation to the support that they provide to the company operators.

4.4.2. TCF and methodology application to the assembly lines production manager

The first example of the TCF methodology application is related to the production manager of the assembly department of Brembo. In order to assess how the introduction of the Industry 4.0 technologies, through the Analytics and Orchestrator tools, changes the work of this specific job profile, some deep investigations have been carried out with the direct observation of the work and semi-structured interviews with the production manager. In particular, the tasks' sets of the production manager before and after the technology introduction have been mapped and used to develop the methodology that is described hereafter.

1. <u>Identification of traditional tasks</u>

In Figure 4.8, the tasks pertaining to the assembly production manager are reported, according to the classification proposed in Section 4.2.

The assembly lines production manager is in charge of the whole department of assembly, which is composed of about 50 manual and semi-automatic lines, which are conducted by one or more operators each. Routinely, the manager organises the shifts of the operator and manages the human resources of the department. These activities employ about the 20% of the total working time and are classified as Routine/Cognitive/Individual tasks. Similarly, the manager performs routine monitoring of the production, in order to control if the production rate is aligned with the target, and produces some reports for the Plant Director with the main KPIs of the assembly lines. The monitoring activity is performed through the direct observation of the line functioning and the reporting grounds on the data collected by the MES and ERP of the company. Totally, monitoring and reporting activities employ the 20% of the manager working time.

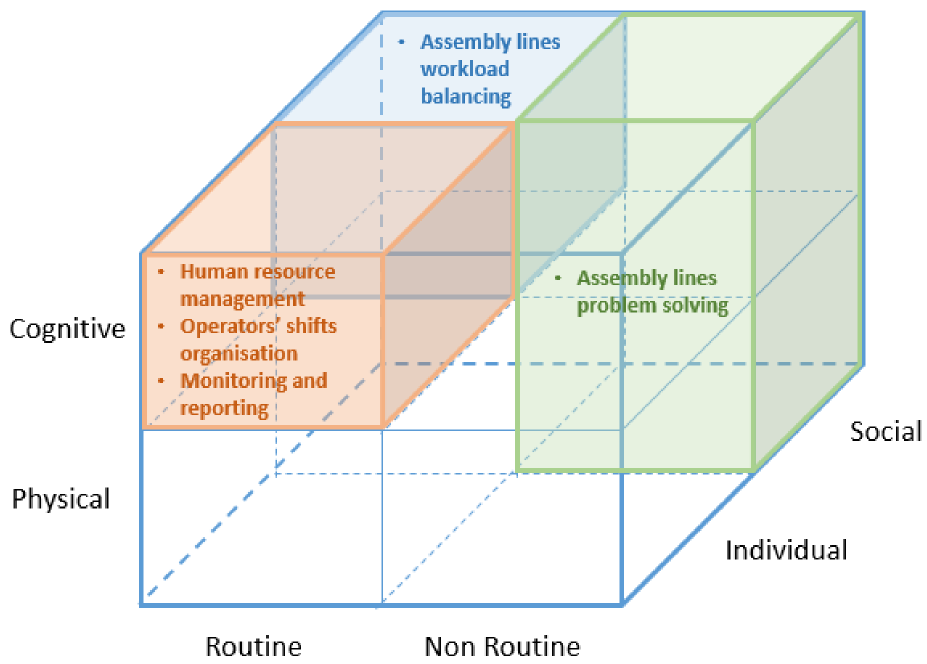

Figure 4.8 – Traditional tasks' set of the assembly lines manager

Finally, other main activities are the assembly lines workload balancing and the assembly lines problem-solving. In the first case, the workload of the department is defined each day based on the customer orders and the availability of the lines and the workforce. This activity is performed by the manager with the support of his deputy and always interacting with other managers (e.g., logistics manager).

In the second case, the manager is in charge of solving the issues that arise during the assembly and may stop the production or create inefficiency and performance losses. This activity is performed interacting with other workers, such as the assembly operators and technicians or the maintenance operators and manager. It involves both a physical activity of investigation on the shop floor and a cognitive activity of cause analysis and problem-solving. These tasks are the most relevant from a time perspective and occupy the 60% of the manager working time.

2. <u>Smart Technologies classification</u>

In the previous section, the Analytics and Orchestrator tools have been briefly described. According to the literature about Industry 4.0 technologies presented in Section 2.2.1, we identify for each of the tool used in Brembo the related Industry 4.0 technologies.

To develop the Analytics tools, Brembo implemented IoT to collect data from the machines and big data and analytics technologies supporting the data aggregation and analysis. Both the technologies have been classified as technologies supporting the cognitive tasks of the operators. In particular, they can support the data collection, communication and analysis. These technologies are particularly useful to improve the monitoring and reporting activities and support problem-solving.

Some examples of the functionality of Analytics are:

- Synoptic visualisation of the assembly lines information:
    - Equipment status (green – working; yellow – no pieces produced in the last 5 minutes; red – no pieces produced in the last 10 minutes)
    - Target and actual cycle time
    - Theoretical and current umber of operators which are currently logged on the line
    - Number of goods and scrap pieces for the current shift
    - OEE and productivity KPIs for the current shift
- Trend analysis of process parameters (e.g., comparison of single parameters filtered by assembly lines, part number, etc.)
- Single –piece traceability information (i.e., all the parameters of a single product assembled, linked with the information about components' batch number)
- Aggregated data about process parameters (mean values and standard deviations, minimum, maximum, etc.).

Some examples of these dashboards are reported in Figure 4.9 and Figure 4.10.

Figure 4.9 – Synoptic visualisation of the assembly lines information

Figure 4.10 – Data analysis dashboards

Orchestrator, conversely, can be defined as a tool enabling the horizontal and vertical integration technology, because it supports the information exchange and the integration among departments and from the shop floor level to the enterprise level. In particular, two main information flows have been digitalised.

The first example concerns the material call process from the assembly lines. When a new order has to be produced on the line, the assembly operator requests the needed material from the warehouse through the ERP system on the line. However, sometimes it occurs that the material is not available, mainly due to suppliers' delays or quality controls that are performed on critical materials in input. Before the introduction of Orchestrator, the operator calling a material that is unavailable needed to go physically to the shift leader office, which is located in the centre of the assembly department, and ask for information. In turns, the shift leader was expected to control why the material was unavailable and directly addresses the specific department (i.e. quality or warehouse) where the material was blocked. It is evident that this process was not optimal, rather it was time-consuming and created a productivity loss because the line operator was required to stop the assembly line and find the shift leader, who maybe was not always present in his office.

The introduction of Orchestrator supports actively the management of the material non-availability in the warehouse. When a line operator calls a material that is not available, Orchestrator immediately informs the shift leader through a widget that is present on his computer or mobile devices. This issue is instantaneously taken into account from the shift leader, who can directly forward the information to the other departments, assigning them a task which is visible on the PCs and mobile devices. In this way, the warehouse operators or the quality inspector can give a fast response to the shift leader about the material, providing the information about if and when it will be available. This answer is automatically directed also to the line operator, who can decide if it is reasonable to wait the material or he needs to start the following production order scheduled for the line.

The second example concerns the detection of anomalous parameters on the assembly lines. In particular, continuous monitoring of the recipes and process parameter constraints is performed and process flow in Orchestrator is started when a deviation of these parameters is identified. This flow is contextually directed to the assembly lines manager and to the quality analyst through the Orchestrator widget. Consequently, they are required to interact to investigate the causes that produced the process parameters deviation and take action to solve the anomaly or fix new settings in the recipes and parameters limits.

According to the smart technologies classification, it is possible to state that Analytics can support cognitive activities that are performed both individually or in team, while Orchestrator specifically supports cognitive tasks that require a social interaction among stakeholders. Both the tools, finally, can support both routine/non routine tasks.

In the following, the impacts of these tools on the work of the assembly lines production manager are discussed.

3. Identification of changing tasks

The introduction of Analytics and Orchestrator changed significantly the work of the assembly lines production manager. The two tools have different impacts on several tasks, and, according to the perception of the interviewed manager, they brought a general improvement in his work life. In Figure 4.11, the new tasks' set of the assembly manager is depicted.

In the figure, some tasks among the ones already performed by the assembly lines manager have been highlighted in yellow. For these tasks, significant improvements in the time needed to perform them have been observed. In particular:

- The *Monitoring* task benefits from the dashboards available in Analytics to have a live visualisation of the production and the status of the equipment. If before the monitoring activity was mainly performed with a direct observation of the machines in the shop floor, after the introduction of Analytics, each day and many times during the day, the assembly manager is able to check the productivity of the department and evaluate if the production is aligned with the target thanks to a department synoptic visualisation.
- The *Assembly lines workload balancing* task has been positively affected as well in terms of responsiveness. Thanks to a more simple monitoring process through Analytics, the assembly manager is able to balance and re-balance during the day the workload of all the lines, in connection with the suggestions from the logistics manager, who can visualise contextually the actual production progresses.
- The *Assembly lines problem-solving* task is now supported by the huge quantity of data which are collected via IoT and aggregated and available for navigation through Analytics. In fact, if previously a physical activity of investigation and data retrieval on the shop floor was required, after the automatic data collection and aggregation performed by the new technologies, this is no more necessary, because data are already available on the web browser. The problem-solving task then is modified in its nature, avoiding physical activity and preferring the cognitive content of the task itself.

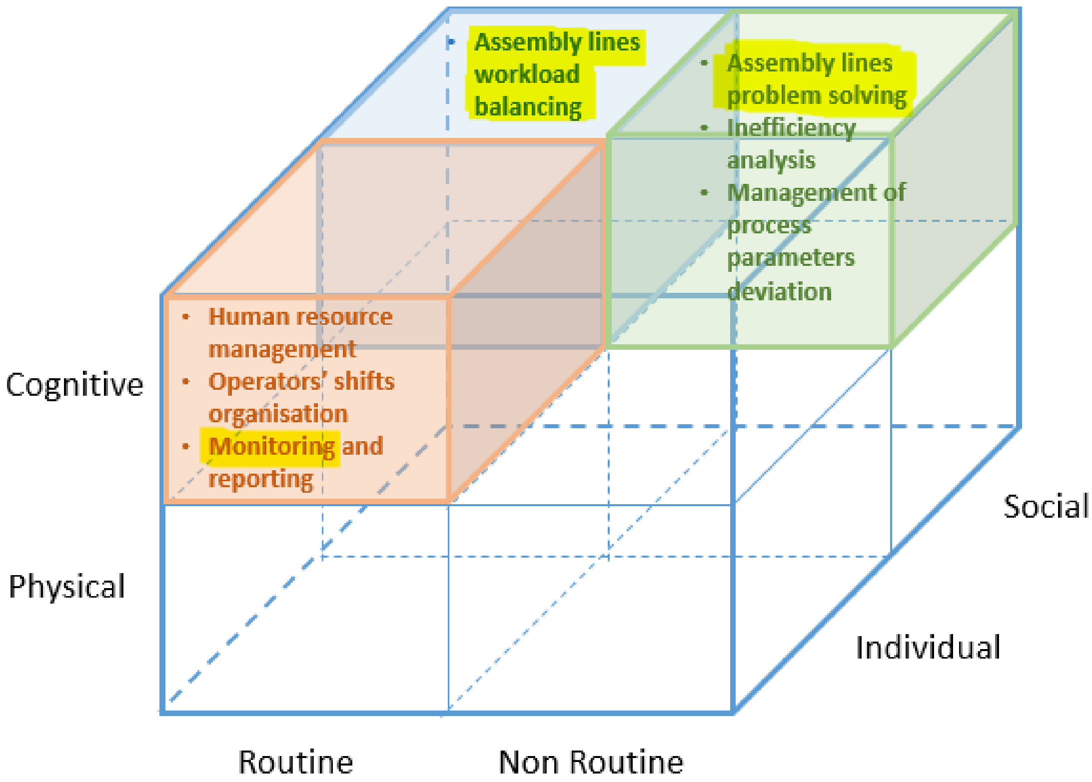

Figure 4.11 – Tasks' set of the assembly lines manager after technology introduction

Along with the improvement in some tasks that were already performed, new tasks appear:

- *Inefficiency analysis* task is related to the possibility of the increased data availability provided by Analytics. As explained before, one of the strengths of the tool is the possibility to link data collected from the assembly lines with the MES and ERP data. This allows to perform new analysis and identify some causes to recurrent issues and inefficiencies which occurs during the manufacturing activities and maybe are related to specific organisational parameters (such as the operator number, the part number, etc.) that before could not be detected. Moreover, thanks to the information flow digitalisation through Orchestrator, a new analysis about the material call process is performed now by the assembly lines manager. In this case, it helps in having an objective view of how this process impacts on the productivity and it helps in the development of strategies to improve the process management, supporting the collaboration with other stakeholders.
- *Management of process parameters deviation* task is related to the new flow managed by Orchestrator which is called "Anomaly detection". Previously, this activity was not performed, while now a notification is sent to the assembly lines manager if an anomalous trend in the process is detected or a deviation in the parameters' boundaries is identified. A new task is then assigned to the lines manager to solve all this kind of issues, also with the involvement of other departments.

Finally, it is remarkable that, also if it has not a direct impact on the tasks set performed by the manager, the interviewed highlighted that the new tools improved the quality of his work. In fact, having the possibility to find easily a structured set of data, with a user-friendly tool to filtered, aggregate and visualise them, positively supports the general management of the department. Moreover, the Orchestrator application positively affects the work of the line operators, reducing the time losses to perform complex information sharing, which before were managed by physical interaction or through emails and phone calls. This, in turns, positively affects the KPIs of the whole department, which are used to evaluate the work of the assembly manager by the Plant director. Therefore, implementing new tools generates also indirect but relevant effects on the work-life of this specific job profile.

4. <u>Re-balancing of the task allocation after the introduction of technology</u>

After the identification of the AS-IS and TO-BE tasks performed by the assembly lines manager before and after the technology introduction, in this step, the evaluation of the changed tasks' set is discussed. It is worth mentioning that, in relation to the recent introduction of the Analytics and Orchestrator tools, it has not been possible to quantify exactly the time which has been saved by the technology introduction. An interesting consideration is about the activities which have been impacted. In fact, the technology introduction mainly impacted the tasks which employ most of the working time of the manager (i.e. Assembly lines workload balancing and problem-solving – 60%). In fact, the interviewed manager stated that the non-routine activities of solving technical and organisational issues of the department are the most time consuming and difficult to manage because they require every time different approaches to solve them. Exploiting the potentials of new data analytics, the manager expects to perform them in an optimised amount of time, also with an improved quality of the solution deployed. For sure, the IoT technology supporting automatic data collection and sharing will replace the physical activity of data retrieval from the assembly lines avoiding the manager to go on the shop floor to collect the data from the control PC of the lines.

From the methodology application, it is possible to observe that, despite a considerable time saving could be expected thanks to the optimisation and improvement of some tasks, at the same time, new activities are assigned to the assembly manager. According to the previous theoretical considerations (see Section 4.3.4), it can be stated that the company strategy is to rebalance the work activities of the workers in order to have a new tasks' set requiring the same time amount compared to the prior situation (in Section 4.3.4, this has been depicted as scenario 1).

In fact, Brembo aims at providing its workers with useful tools to relieve them of low value-added activities, such as data collection and physical on-field investigation, in order to encourage them to perform more complex and cognitive activities, requiring advanced technical and methodological skills, which may have long-term effects in improving the whole process and therefore the plant performances. In particular, the time that can be saved avoiding no-value added activities should be employed in the analysis of data to identify predictive strategies to manage the possible inefficiencies in the production, both related to technical problems (i.e. maintenance issues) and organisational problems (i.e. human resource management, supply chain management and production planning).

In doing this, however, the company and all the stakeholders in the enterprise involved in the introduction of new technologies are aware of the need to upgrade and mature new skills and competences, requiring proper training strategies. This will be the focus of the next section.

4.5. Discussion: technology is upskilling or deskilling?

The evaluation of how the Industry 4.0 technologies affect the work of human operators in the enterprise is necessarily linked to the discussion about the changing skills which are required to manage new ways in performing usual activities and new tasks that emerge. Despite this topic will be extensively discussed in the next chapter (Section 5), some preliminary considerations about the insights provided by proposed methodology and the case study results are reported hereafter.

Both the literature and the Brembo case suggest that, according to the transformation in the tasks' set of specific job profiles, a different perspective of competence and skills development can open up for the workers. If it is widely accepted that technology (and in particular all those technologies which are able to automate human tasks) is expected to replace the activities characterised by physical content and mainly performed routinely and in a standardised way, there is still a debate about how to manage new and changing tasks that are related to improvement opportunities brought by new technological implementations, which will enlarge conversely the non-routine and cognitive tasks field.

As a matter of fact, automation in the last two centuries has not induced a long-run increase in the unemployment rate and not even made human work obsolete but it "complements labor, raises output in ways that lead to higher demand for labor, and interacts with adjustments in labor supply" (Autor, 2015). In particular, today, the advent of advanced robotics, digital technologies, smart machines and artificial intelligence can replace some tasks, but at the same time is creating an emergence of new tasks ranging from engineering and programming functions to those performed by audio-visual specialists, executive assistants, data administrators and analysts, meeting planners, and social workers (Acemoglu and Restrepo, 2018).

Since the last century, a relevant debate on the issue of deskilling of workers has been at the centre of many researchers' work in the field of labour studies, starting from the Braverman's thesis about the link between the division of complex tasks into simple steps (e.g., Taylorism) and the "secular" trend to deskilling of workers in the name of increased managerial control (Braverman, 1974). The Braverman's work has been reviewed and criticised (Attewell, 1987; Elger, 1979), while many other scholars took inspiration from it to support the idea that automation brought negative consequences to the human work content and organisation(Kraft, 1979; Wallace and Kalleberg, 1982).

Nowadays, the deskilling perspective, which represent a degradation of work in relation not only to the automation but also the digitalisation, is strongly contrasted by an upskilling approach, aiming at preparing workers to face increasingly challenging tasks. Upskilling the workers means to raise and augment their knowledge (Bravo, 2015) and require a joint effort from companies, education systems, and governments. Upskilling can be further declined into cross-skilling, which is acquiring new knowledge in other fields respect to the current tasks, re-skilling, which is an update of current skills, and expert-skilling, which refers to gaining a deeper knowledge about the currently performed tasks' domain. All these approaches can be developed simultaneously, in order to align the workers' competences to their new tasks set after the technology implementation.

4.5.1. How to support the upskilling perspective?

The Task Classification Framework and the related methodology represent a useful tool that companies can adopt in a preliminary step of digital transformation to the identify the new requirements in terms of skills and competences which are related to the technology adoption. In fact, the upskilling approach requires companies to make some efforts in depicting proper strategies to train and retrain workers. Companies will have to act on several fronts, not only with classroom-based lessons but also including on-the-job-training, for instance with the use of digital technologies (e.g., augmented reality) or with the help of more experienced workers. Since more workers will be employed on different tasks, it will be essential to provide training on a wider set of skills (i.e., cross-skilling). In this context, the interaction between universities and companies should be increasingly promoted. In fact, universities should play a fundamental role in supporting companies towards the connected and digital technologies paradigm. The support companies need, in fact, has as its core the continuous training of people, or lifelong learning, which is expressed in two moments. At first, it finds its form in the development of classic training offers, such as in-class training, which is increasingly offered by universities at companies also through the creation of corporate academies, which provide specific training courses on digital technologies and new operational mechanisms proposed by the paradigm of Industry 4.0. This type of training allows the first fundamental step for the literacy and retraining of workers. In a second step, continuous training in the field is promoted, using methods such as on-the-job training and learning by doing, which involve an active role for workers in carrying out innovation projects applied to their own business context. Collaboration between universities and companies in this field often results in the construction of shared laboratories, the so-called joint labs, in which teaching, research, technology transfer and innovation merge. In this context, the knowledge of the academic world is combined with the know-how of the industrial world to promote a constant updating overtime of the workforce skills. Further ways of fruitful interaction between university and company are the industrial research PhD programs, effective both for the company, which benefits from highly qualified human resources to carry out its innovation projects, and for the academic world, which has the opportunity to do applied research in a real industrial context.

4.5.1. Managing the upskilling in Brembo

The TCF methodology applied to Brembo previously showed how the company is trying to rebalance the tasks' set of job profiles impacted by the technology introduction promoting the upskilling of workers. In particular some of the aspects reported in the previous paragraph have been observed in the company.

Company academy and training activities

Since 2008, Brembo has developed an internal academy, which was established to promote the Lean Production paradigm. The first Lean Laboratory, which is called Brembo Production System Lab (BPS Lab), has been built In the Italian plant and then it has been exported and reproduced in eight other plants worldwide. The BPS Lab has been created in order to provide workers with a continuous and structured training offering, based on theoretical and practical modules.

After the recent technological innovations, the BPS Lab has been redesigned to cater for two core types of *lean-training,* the first for the more traditional human-intensive areas such as manual production and assembly operations, and the second for more Industry 4.0 relevant, capital-intensive areas like robotics and automation.

Moreover, augmented and virtual reality technologies have been introduced to train the production operators and the maintenance technicians. In particular, VR has been used to train the technicians in the Mexico plant to assemble a specific assembly line that was transferred from the Italian plant. Before the assembly line transfer, indeed, the 3D model of the line and the 3D representation of the assembly and installation activities have been developed in a virtual environment. Using these virtual instructions, the Mexican technicians have been allowed to visualise and learn the assembly sequence in advance and when the line arrived in the plant, they were already trained about the tasks to accomplish to install all the equipment, saving a relevant amount of time.

In line with this, the new production systems that are designed by the internal process development department of Brembo are released jointly with the 3D instructions both for installation (i.e., for the technicians) and usage (i.e., for the production operators).

Finally, along with the BPS Lab activities, the corporate training offering has been enlarged and new courses have been introduced, related to the data science field, to cope with the increasing needs of managing data and information from the plants.

According to the opinions that have been collected by the author during the years spent in Brembo, all these improvements in the training offering have been positively accepted by the employees and an increasing number of workers is becoming aware of the importance in updating their own skills to fully exploit the potentials of the new tools and technologies introduced.

University-Company collaboration

Brembo is involved in the collaboration with universities for research projects for many years. In particular, the already cited “Smart Manufacturing 2020” project has been the starting point for the digital transformation of the company, as it involved several partners with complementary competences and capabilities to develop a roadmap of technology implementation and process transformation towards smart manufacturing. In particular, during the project's activities, the author was allowed to collect useful insights to develop the PhD research. From the academic perspective, dealing with the day-by-day issues of an industrial company, in fact, has been useful to understand the relevant human aspects to consider when introducing new technologies and providing managerial implications to the proposed approaches.

At the same time, the company benefited from the presence of a researcher focussed on the observation of the workability and manageability of the new technological implementations, able to provide an objective view and an external evaluation of the impacts on the operators' activities.

4.6. RQ1 outcome

This chapter aimed at answering to RQ1:

How do smart technologies affect the tasks of the operator in the context of Industry 4.0?

To answer this first research question, a task analysis approach has been developed. In particular, to assess the specific impacts of the new technology adoption on the human work, the task approach has been deemed as a suitable opportunity to decompose the human work into less complex units, more simple to analyse. As explained in the introductory paragraph of the chapter, also some relevant literature contributions supported and justified this choice.

Therefore, first, in the chapter, a Task Classification Framework has been presented. Three main relevant classification dimensions have been discussed, namely routine/non-routine, physical/cognitive, social/individual tasks' features. The aim of the classification was to provide a structured framework in which the tasks' set of specific job profiles could be represented, in order to later assess how the technology changes it. Subsequently, based on this TCF, a methodology to assess the impacts of technology on human tasks have been described in four steps, which are i) the identification of traditional tasks, ii) smart technologies classification, iii) identification of changing tasks, iv) rebalancing of the task-allocation after technology introduction.

In order to provide an example of the practicability of this approach, the methodology has been applied in a real industrial company. An action research project has been developed during the PhD program in collaboration with Brembo, which is an Italian large manufacturer of braking systems. During the time that the author of this thesis spent in the company, some new technologies and tools supporting human operators have been conceived and implemented, in order to improve the employees' work life. From the project, several insights emerged and were really useful to gain a comprehensive view of the research topic. The TCF methodology has been applied to one of the most impacted job profile of the company, i.e. the assembly lines production manager. From the tasks' analysis before and after the technology implementation, it emerges that the new tools introduced in the company successfully supported the work of the manager. In fact, technology generally improved and optimised simple and routine activities such as monitoring and data collection, but at the same time created new opportunities of data analysis, able to improve the overall performance of the department.

Beyond the specific example, it has been discussed that Industry 4.0 technologies are expected to replace routine and low added value tasks, rather enlarging the tasks' set concerning the cognitive and non-routine field, which in the long-term can provide companies with an increased knowledge of their production processes and with preventive capabilities, enabling in turns flexibility.

However, grasping the improvement opportunities that the technological change offers poses numerous challenges for companies, among which the qualification and skills of operators in particular emerge. Only by analysing them and rethinking the global context it will be possible to ensure that technology is not de-skilling for the workforce, but on the contrary can increase its capacity, in an up-skilling perspective in which operators plays an active and increasingly decisive role in the industrial context. Several strategies for training and re-training employees can be suggested and the Brembo case demonstrated that only involving a general perspective and a strategic training offering, companies can successfully help workers to align their profiles with the new tasks' requirements.

Further investigations about the new competences and skills for the Industry 4.0 era will be the focus of the next chapter.

4.6.1. Relationship between RQ1 outcome and the other RQs

According to the whole thesis research objectives, that have been presented extensively in Chapter 3, the RQ1 aimed at exploring the perspective of Human-Technology interface of the HTO model (see Figure 3.1). The presented RQ1 outcome, namely the TCF and its related methodology, contributes to providing a first tool to assess how the technology adoption push the re-arrangement of working activities performed by humans. In doing this, then, the RQ1 outcome is strictly linked and preparatory to the RQ2, whose objectives concern the exploration of competences and job profiles in the context of Industry 4.0. The definition of the new tasks' set of "Operators 4.0", in fact, highlights the modes of human-technology interaction, revealing the emerging needs in terms of workers' skills and competences. At the same time, the characteristics of the new tasks, in particular according to the distinction between cognitive and physical tasks, suggests that the nature of human work undergoes changes, in terms of flexibility, specialization and polyvalence. Therefore, the results of the first RQ reinforce the research needs related to RQ2.

Finally, the results of RQ1 will be a starting point for the development of a more general framework for the integration of human and technology in the smart factory, the subject of QR3.

5. NEW COMPETENCES AND JOB PROFILES FOR INDUSTRY 4.0

After discussing the Human-Technology interface of the HTO model, this chapter aims at analysing the impacts of Industry 4.0 technology introduction on the nature of work. In the literature about work design, the main characteristics of a work/job have been named also work attributes (Das, 1999), which encompass motivational job characteristics, such as autonomy and specialisation, knowledge characteristics, such as problem solving and skill variety, social characteristics, such as interdependence and interaction, and contextual characteristics, such as the usage of technology (Morgeson and Humphrey, 2006). As a consequence to the evolution of tasks that has been discussed previously, Industry 4.0 and digitalisation are expected to bring changes in these work attributes, requiring further investigation about how the nature of work will change (Richter et al., 2018). To evaluate this, in this chapter the impacts of Industry 4.0 technology on job profiles and organisation and consequently on the skills and competences of workers, referring to both the two interfaces Technology-Organisation and Human-Organisation of the HTO model, will be considered, based on the assumption that the work attributes that characterise the work can be summarised in this three main areas (i.e. job profiles, organisation, competences).

In the first section, an overall presentation of the topic is reported, based on literature, to provide the background of the developed research.

In the following sections, two case studies' analyses are discussed, in order to provide an answer to RQ2. In the first multiple case study (case study A), ten small and medium manufacturing companies located in the North of Italy have been interviewed, in order to understand how the introduction of new Industry 4.0 technology affected the organisation structure of the company along with the job profiles and the related workers' competences. In the second multiple case study (case study B), eight companies operating in the machinery sector and located in northern Italy have been involved, with the focus on their activity as service and product-service providers, with the aim of identifying, also in this case, the most relevant competences to leverage smart technologies to successfully undertake the business transformation which is called digital servitization.

In Sections 5.2 and 5.3 the methodology and the results of the two case studies are detailed.

5.1. Background

Since many years, literature suggested the need to couple the introduction of new technologies with the organisational development (Riis and Neergaard, 1995). The strong link between the technological innovation (both in products and processes) and the organisational variables had been already postulated in the model proposed by Abernathy and Utterback (1978). As stated also previously by Utterback (1974), there is evidence that some organisational structures and characteristics positively affect the success of innovation and technology introduction. For this reason, different organisational learning approaches have been discussed in the Operations Management community (Argyris and Schön, 1997; March, 1991; Senge, 1990, 1994), conceiving organisations as entities able to "learn" as the collective patterns of behaviour amongst organisational members change and adapt to their environment (Rhodes, 1996). Later, Drejer (2000) extensively discussed the relationship between organisational learning and competence development, arguing that the first can be considered as the starting point to an effective competence model formulation, given the importance of the human learning capabilities in the process of acquiring new knowledge to become more "competent" .

More in detail, the socio-technical literature addressed the co-evolution of technology and organisation focusing on micro-level impacts on tasks and job roles (Leonard-Barton, 1988; Trist and Bamforth, 1951). Socio-technical design principles have been also proposed by Cherns (1976).

The literature concerning the relationship between organisational and human aspects following the introduction of new technologies is reported as not been sufficiently explored within the Industry 4.0 concept (Charalambous et al., 2015).

The task approach has been used in the previous chapter to depict how technology reshapes and changes the tasks of the humans in the smart factory context. The evolution of job roles, on the other hand, represents the focus of investigation inside the Technology-Organisation interface of the HTO model.

In the debate on how the Industry 4.0 technology impacts on the organisation, many contributions started to focus on the evolution of job roles and their specific tasks (Gehrke, Lars et al., 2015; Kagermann et al., 2013), while others are now moving their attention towards the macro-level impacts on companies' organisation. Gehrke et al. (2015) envision that "*the organisation of a factory of the future will be more flexible, changeable, decentralised, and not as deterministic as the organisations of today",* and Shamim et al. (2016) take a step further, by suggesting the suitable organisational structures to embrace the Industry 4.0 paradigm. In particular, an organic design, characterised by decentralisation, empowerment, low formalisation, and collaboration, is assumed to be more suitable for an innovative and changing environment. Furthermore, some specific organisational structures have been identified as facilitators of Industry 4.0, such as the matrix and the team-based structures, specifically designed to have a flat hierarchy and a high decentralisation (Shamim et al., 2016).

In the scientific community, it is widely recognised that technology and organisation need to co-evolve in order to let the latter be ready to embrace the new roles and tasks created by the technology introduction. However, to properly catch the dynamic changes in organisation moving toward Industry

4.0, a joint investigation of the TO interface with the HO is required. The holistic view over the three HTO dimensions allows identifying the most relevant challenges and opportunities generated from the Industry 4.0 paradigm.

5.1.1. Competence models for Industry 4.0 in literature

Along with the evolution of organisational structures and job profiles, workers' skills and competences appear to be directly impacted by Industry 4.0.

In literature, the competence development has always been considered of utmost relevance for organisations to achieve a competitive advantage (Tampoe, 1994). The formalisation of specific competence models for workers has been addressed by many researchers in the Human Resource Management (e.g. Hagan, 1996; Lawson and Limbrick, 1996) research stream and often the competence theory has been related to the Operations Management (Kim and Arnold, 1993; Lewis, 2003; da Silva Gonçalves Zangiski et al., 2013), highlighting the impacts that a proper competence development has on the performance of the enterprise operations.

In literature, some competence models, studying the new competences needed within an Industry 4.0-oriented organisation, are emerging. More in detail, starting from 2011, Davies et al. (2011) identify six drivers of change, which are expected to have a disruptive effect on the future of work. They include both technological advancement, such as the rise of smart machines or the computational world, and social trends, such as the longevity of the workforce. In relation to them, a set of ten soft skills is discussed, encompassing social intelligence, transdisciplinary, sense-making, adaptive thinking, and so on. Gehrke, Lars et al. (2015) provide a more detailed competence framework by classifying the skillset of future workers in technical and non-technical qualifications. Another holistic approach, including a wider variety of skills, is presented in Hecklau et al. (2016), where starting from external challenges and trends affecting the industrial scenario, a competence model, in which competences are grouped in four classes - technical, methodological, social and personal competences - is suggested. Also, Erol, Jäger, et al. (2016) propose a categorisation of competences into personal, social/interpersonal, action-related and domain-related ones, distinguishing on the same time the required competences for different workers' level, such as engineers or managers. Another approach presented in literature to develop competence models is by referring to precise job profiles of specific enterprise's areas. For instance, Prifti et al. (2017) consider three main areas of application, i.e. Information Systems, Computer Science and Engineering, and identify for each the required skillset. Similarly, Pinzone et al. (2017) focus on the technical skills in five organizational areas, the Operations Management, Supply Chain Management, Product-Service Innovation Management, Data Science Management, and IT-OT Integration Management. Moreover, Industry 4.0 skills overall overviews, based on a systematic literature review, are provided by van Laar et al. (2017) and Janis (2018). Interestingly, all these contributions highlight the need to balance technical skills, related to technology knowledge and usage, with soft skills, which are recognised as fundamental to stimulate a change in the organisation (Rehman et al., 2014).

5.2. Exploring job profiles and competencies for Industry 4.0 in manufacturing companies

As discussed before, a joint investigation about the impacts of Industry 4.0 technologies on competencies, job profiles and organisation structures can provide a better understanding of how Industry 4.0 will change the nature of work in the manufacturing. To properly answer the RQ2, in addition, the case study research has been identified as a suitable approach to perform exploratory investigations for phenomena, which are not fully understood, and require the development of theory (Karlsson, 2008).

5.2.1. Development of a conceptual framework

As a first step of this research, in order to extract from the case studies the relationships between technology implementation and competences, job profiles and organisation structures, a conceptual framework has been designed. It represents a fundamental step in the design of empirical research (Voss et al., 2002) clarifying the relevant aspects that have to be studied (Miles and Huberman, 1994).

The conceptual framework of this research, represented in Figure 5.1, was grounded on the theoretical models presented in the literature (Emery, 2000; Galbraith, 2002), as well as the seminal works of Leavitt (1965). Coherently with extant models on organization design, four dimensions are modelled as strictly interdependent and simultaneously changing to obtain a successful organizational change, including organisation aspects, both at macro and micro level, technology capabilities, and competences.

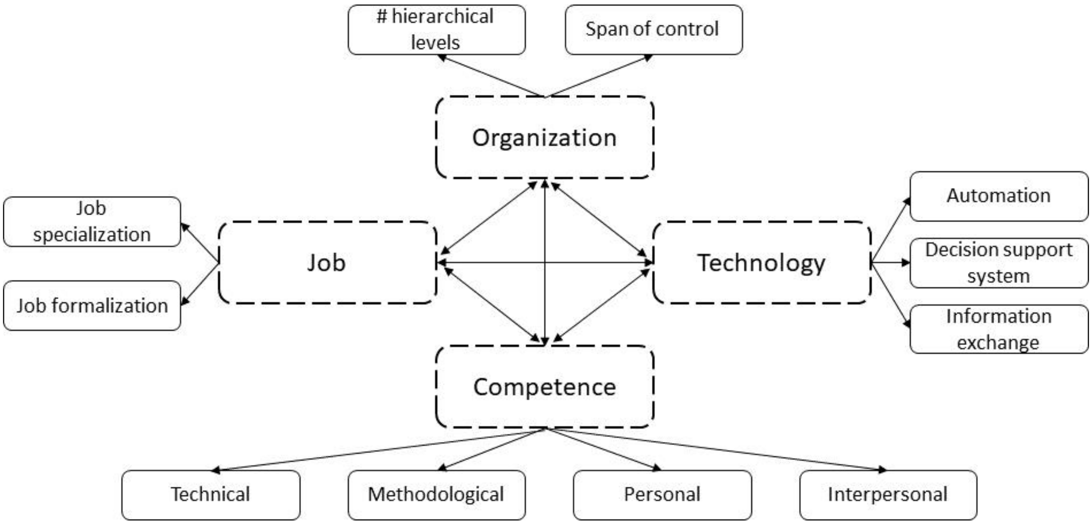

Figure 5.1 – Multiple Case study A: Conceptual framework

Each dimension, in turn, is characterised by several variables, which are the specific features that are investigated through the case study analysis. A short description of the four dimensions and the related variables is presented in the following.

- **Technology.** The main features that characterise this dimension have been identified reviewing the literature about theoretical concepts in Industry 4.0. In particular, starting from the four design principles postulated by Hermann et al. (2015) - namely Interconnection, Information transparency, decentralized decisions, and technical assistance - and the characteristics of Smart Manufacturing technologies identified by Mittal et al. (2016) - such as context awareness, modularity, heterogeneity, compositionality and interoperability - three main features of technology have been included in the framework:
    - *Automation* includes the potentials of advanced manufacturing systems in performing high productivity production processes exploiting the intelligence embedded in machines and equipment, which become Cyber-Physical Systems. Referring to the above-mentioned Industry 4.0 principles, for example, automation is ground on the features of technical assistance, information transparency, and modularity.
    - *Information exchange* concerns the connection and communication capabilities enabled by IoT technologies, which improve the level of collaboration and enable real-time data exchange among information systems and humans. Interoperability and standardisation among devices and systems, which are the main challenges for the implementation of Industry 4.0, are crucial to realise an effective information exchange implementation.
    - *Decision support system* encompasses the analytics and optimisation potentialities offered by data analysis and visualization, supporting operations management and

providing the decision-making with increased responsiveness. The conversion of data from several sources into information and knowledge can advantage decentralised decisions and improve context-awareness.

- **Competences**. The competence dimension, which is similar to Galbraith's (2002) 'People' dimension, includes aspects related to the skills employees need to be productive in their I4.0 organisations. Although several definitions of competence have been reported in literature, in this study we consider a competence as *"a set of characteristics (e.g. skills, knowledge, attitudes) than an individual possess or need to acquire, in order to perform an activity within a specific context"* (Sampson and Fytros, 2008). Based on the competence model provided by (Hecklau et al., 2016) and reported in Appendix A, four categories of competences are considered:
    - *Technical competences* including state-of-the-art knowledge, such as automation, IT and data analysis;
    - *Methodological competences* including the abilities to manage situations and problems, such as problem solving and decision-making;
    - *Personal competences* encompassing individual attitudes, such as motivation, flexibility, self-organisation;
    - *Interpersonal competences* related to social interactions and abilities in communication and cooperation with others.
- **Job.** The job dimension, related to Galbraith's (2002) 'Process' dimension, pertains to the design of positions within an organisation. It is, therefore, connected to the roles played by humans and their individual positions, namely the job profiles (Mintzberg, 1989). From the literature analysis about Industry 4.0, it is not clear if the introduction of new technologies will change the nature of work toward skill polarisation - i.e. assuming a replacement of medium-skills jobs that will be substituted by automation - or towards an upgrading of job skills and jobs, with the creation of new roles as decision-makers and coordinators (Hirsch-Kreinsen, 2016). To investigate these aspects, three relevant variables have been chosen:
    - *Job specialisation*, including horizontal (i.e. the number of different tasks performed) and vertical (i.e. the control over the performed tasks and the level of autonomy) specialisation;
    - *Job formalisation*, related to the standardisation of the work processes;
    - *Training*, concerning the methods used to provide workers with the required knowledge to perform a specific job.

- **Organization.** The organisation dimension, related to Galbraith's (2002) 'Structure' dimension refers to the organisation's architecture and, thus, the location of decision-making power. The organizational structure of a company is defined according to two variables:
    - *Number of hierarchical levels* or vertical span is defined as the number of job positions in line chain of command, from the chief executive to the employees working on the output (Child, 1972).
    - *Span of control,* measuring the boundaries in the hierarchical authority practised by a single manager, influencing the closeness of contact between superior and subordinates (Ouchi and Dowling, 1974) and affecting the number of positions grouped in a single organizational unit (Mintzberg, 1989).

5.2.2. Multiple Case study A: selection and interview protocol

To study the interdependencies and relationships among the four dimensions of the conceptual model, a multiple case study research has been carried out. This activity has been conducted within the project "Competenze 4.0", in collaboration with Confindustria, the largest Italian industrial association. According to the advice of Confindustria and adopting a judgemental sampling (Henry, 1990), a group of ten companies, representative of the main industrial sectors in the North of Italy, has been selected, including small-medium enterprises that are undertaking investments in Industry 4.0 technology.

The multiple case study has been conducted through in-depth semi-structured interviews, according to the research protocol reported in Appendix B, and, when it has been possible, through direct observation of the production process of the involved companies. A description of the company demographics is reported in Table 5.1.

Company	Location	Turnover	Employees	Industrial Sector
A	Bergamo	< 20 M €	<100	Manufacture of electrical equipment
B	Bergamo	20÷50 M €	100÷200	Manufacture of machinery for beverage
C	Treviso	20÷50 M €	<100	Manufacture of food machinery
D	Pordenone	< 20 M €	<100	Manufacture of machinery and equipment
E	Bergamo	20÷50 M €	100÷200	Manufacture of basic metals
F	Pordenone	< 20 M €	<100	Manufacture of machinery and equipment
G	Milano	< 20 M €	100÷200	Manufacture of textiles
H	Treviso	< 20 M €	<100	Industrial automation
I	Bergamo	20÷50 M €	100÷200	Manufacture of machinery and equipment
J	Treviso	20÷50 M €	100÷200	Manufacture of furniture components

Table 5.1 – Case study A: Company demographics

The research protocol adopted during the interview was divided into four sections, related to the four dimensions of the conceptual models, in order to understand first the Industry 4.0 technologies' adoption inside the company and then to assess the impacts of the technology introduction on the macro- and micro- organisational variables and on workers' competences.

Six Industry 4.0 technologies, which have been inductively selected from the interviews' results, have been considered and related to the three variables of the Technology dimension included in the conceptual framework:

- *Automation* variable includes *Advanced Manufacturing Solutions*, which encompasses smart sensors and cyber-physical systems, and *Advanced Robotics*;
- *Information exchange* variable includes *Internet of Things and Big data*, and *Cybersecurity*;
- *Decision support systems* variable includes *Simulation* and *Augmented reality*.

The technology adoption has been evaluated according to a six-stage scale defined as follows:

1. *Non-use,* if the company has very low or null knowledge about the technology;
2. *Orientation*, if the company is evaluating the introduction of new technology in relation to its business models and workers competences;
3. *Preparation*, if the company is conducting initial activities to introduce the technology;
4. *Testing*, if the company is starting assessing the impacts of the technology introduction;
5. *Routine*, if the company is already adopting technology in standard processes.
6. *Refinement and integration,* if the company is undertaking actions to optimize and improve the technology usage and integration in their processes.

Concerning the impacts on technology on job profiles, organisation and competences, the interviews aimed at exploring how technology affected the nature of work in the company. In particular, the job analysis addressed the topic of individuals' working contents and roles, identifying if new positions were created in the company. Moreover, changes in the variety and volume of tasks for existing positions have been explored, along with changes in other work attributes, namely work features, such as speed in the task execution, hierarchical control, responsibilities, specialisation, autonomy, etc. Strictly related to job analysis, competences have been explored, both for existing and new positions. Finally, the observation of organisational charts and investigation of the hierarchical levels in the companies jointly with the decision-making power for managerial roles provided valuable insights to analyse the impacts of technology introduction over the macro organisation of the enterprises.

A summary of the case study research is reported in Table 5.2.

Who conducted the case study?	Each case study involved at least two researchers to achieve reliability and validity
What are the methods used to conduct the case study?	Interviews, direct observation and document analysis
When did interviews take place?	In 2018
How many companies have been involved?	10 manufacturing companies
What was the aim of the interviews?	Investigate the investments in so-called Industry 4.0 technologies to bring out: • The birth, evolution and disappearance of roles and tasks • The impact of the adopted technologies on the skills required of workers • Organisational changes introduced by technology adoption • Expectations and issues related to investments
What were the topic addressed in the interviews?	• General data about company business (e.g. dimension, workers, customers) • Industry 4.0 Technology investments • Impacts of technologies on organization (macro and micro level) • Impacts of technologies on competences

Table 5.2 – Case study A: Summary

5.2.3. Multiple Case study A: results

The case studies' analysis provided relevant contribution to outline the impacts of technology on the nature of work and thus answering to RQ2. In the following, the results of the case study are reported.

Technology

First, a summary of the technologies adoption is presented in Table 5.3.

From the table, it emerges clearly that the involved companies mainly promoted investments in Advanced Manufacturing Solutions and IoT and Big Data technologies. Indeed, most of the companies are introducing into their processes new smart and connected machines, embedded with smart sensors and able to perform multiple data acquisition. Because of smart machines implementation, new infrastructures for data communication are required, which is the reason why IoT is the other most relevant and adopted technology. Along with IoT, proper strategies to manage all the data collected from production processes are critical. The third most adopted technology is simulation, which refers both to product simulation, supporting the engineering phase, and process simulation, aiming at modelling and conducting what-if analysis of the production environment. Concerning the other technologies, definitely limited adoption has been observed.

Company	Advanced manufacturing solutions	Augmented reality	Advanced robotics	Simulation	IoT and big data	Cybersecurity
A	5	1	1	4	5	5
B	3	1	1	2	3	1
C	3	6	4	1	6	2
D	1	1	5	5	5	1
E	4	1	1	3	2	2
F	5	1	1	1	5	1
G	4	1	1	1	3	3
H	3	4	6	1	4	1
I	1	1	1	1	1	1
J	3	1	3	2	1	1
Mean	3,2	1,8	2,4	2,1	3,5	1,8

Legend
1 - Non-use
2 - Orientation
3 - Preparation
4 - Testing
5 - Routine
6 - Refinement and Integration

Table 5.3 – Case study A: Technology adoption results

Competences

Second, the new competences relevant to support the technology introduction have been analysed.

Among technical competences, companies underlined the importance of advanced use of IT, not only concerning physical devices (e.g. computers, mobile devices, PLCs) but also related to the efficient use of software solutions, such as ERPs, MESs and other departmental information systems. Other skills such as data analysis and programming are envisioned as crucial to manage data and convert them into information useful to undertake actions.

Also, methodological competences, such as problem-solving, project management, change management, knowledge management have been reported as the most required to evolve towards Industry 4.0. In addition, decision-making skills and abstraction abilities are useful for defining and pursuing short- and long-term objectives for the enterprise.

Within the personal competences, the interviewed firms stated that leadership and ability to transfer knowledge to others are the most relevant skills, followed by an open mindset, critical thinking, creativity, and systemic vision of situations.

Finally, considering inter-personal competences, many companies agreed to arguing the relevance of social competences, such as collaboration and information sharing are relevant, followed by team working and networking capabilities.

In analysing these results, it has been useful to abstract if the competences identified as relevant in the Industry 4.0 are already present in the company, are under-development through training actions or conversely no effort is spent at the moment to their development. The results are shown in Figure 5.2.

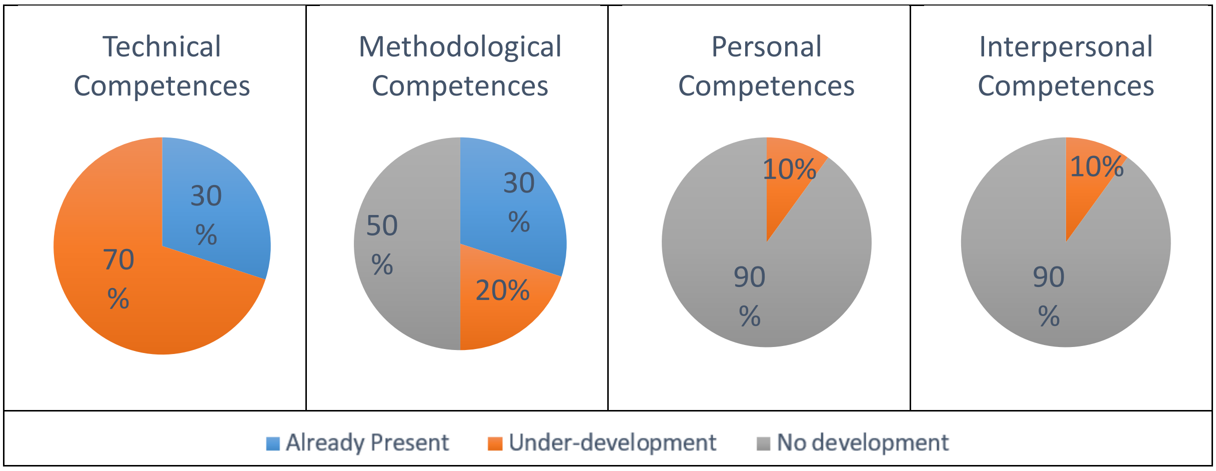

Figure 5.2 – Case study A: Competences' development analysis

According to these results, it is possible to state that the competences development is not uniform into the four categories. For instance, it appears clearly that all the companies are introducing training activities to upgrade technical skills of the employees (if they do not have already technical competences present), while only the 10% of companies are planning to develop personal and interpersonal competences, demonstrating that different levels of importance for each category are perceived by the companies. Combining this analysis with the above-discussed technology adoption results, it is possible to provide evidence of the relationships between technology introduction and competence development. All the interviewed companies, regardless of their level of adoption, agreed in highlighting the need for technical competences, which are primarily affected by new technology introduction. For instance, in acquiring and installing advanced manufacturing solutions in the shop floor, the companies need workers able to integrate and use the new machines and related devices in short time. For this reason, in the first stages of technology adoption, they are more focused on developing technical skills and, only in the following, they manifest the need of methodologies, organisational and human aspects useful for effectively integrate the technology in the production. In addition, these kind competences are more critical to acquire and higher effort is required to change people's and organisation's behaviour according to the new production paradigms.

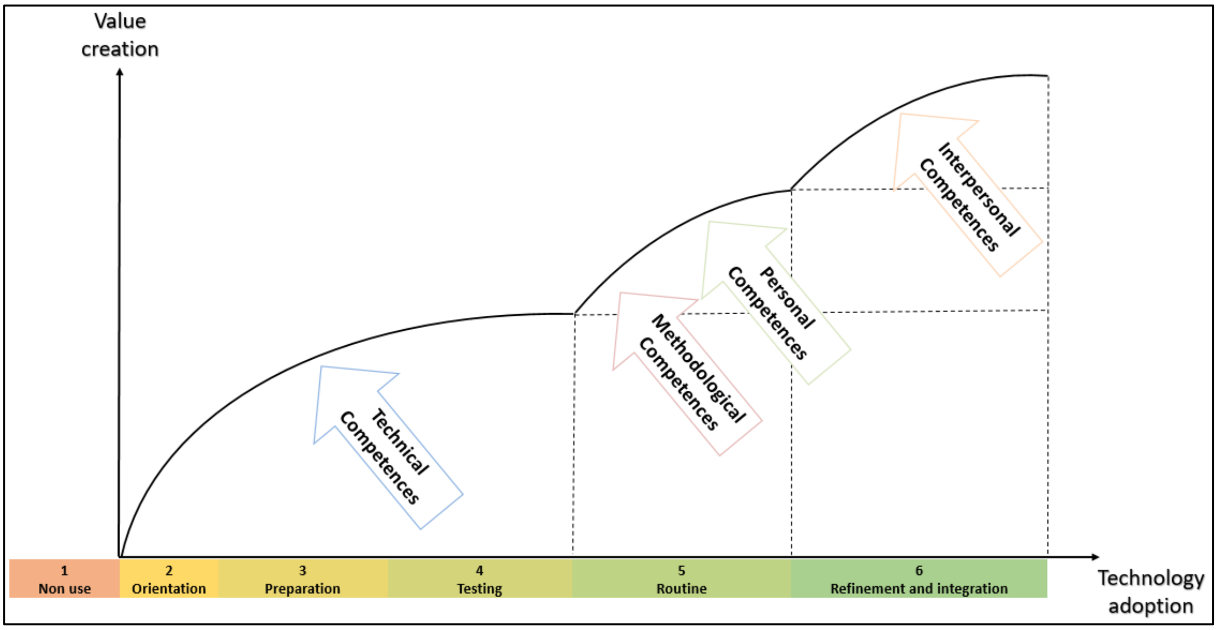

Figure 5.3 – Multiple Case study A: Relationship between technology adoption and competence development

According to the previous discussion, in Figure 5.3 the relationship between technology adoption and competence development has been represented.

Job

The exploration of how Industry 4.0 technology is changing human roles and positions (i.e. micro-organisation aspects) inside the companies has led mainly to the analysis of two relevant aspects: polyvalence and specialisation. In literature, polyvalence is defined as the ability to perform a variety of tasks in relation to the company's needs (Camps et al., 2016). Polyvalence can also be referred to as the horizontal mobility among tasks. The interviewed companies stated that with the introduction of new technologies, employees are required to enlarge their tasks, and in many cases this is related to the need for managing several IT systems and devices. In addition, also specialisation is considered of utmost importance to both acquire deep experience and ability in the work, that is vertical specialisation, and augment workers' decision-making autonomy, that is horizontal specialisation, which is supported by the increased number of data and information that can be accessed.

Moreover, consequently to this need of polyvalence and specialisation features, new job positions have been created in the companies. They concern operational roles (e.g. automation specialists; software and data scientists; industrial designers) and managerial ones (e.g. product manager, project manager, process owner). Also in this case, training has been recognised as essential to provide people with suitable competences to fit new job profiles.

A summary of the job profiles, grouped in 5 areas, which are required by the interviewed companies is presented in Figure 5.4.

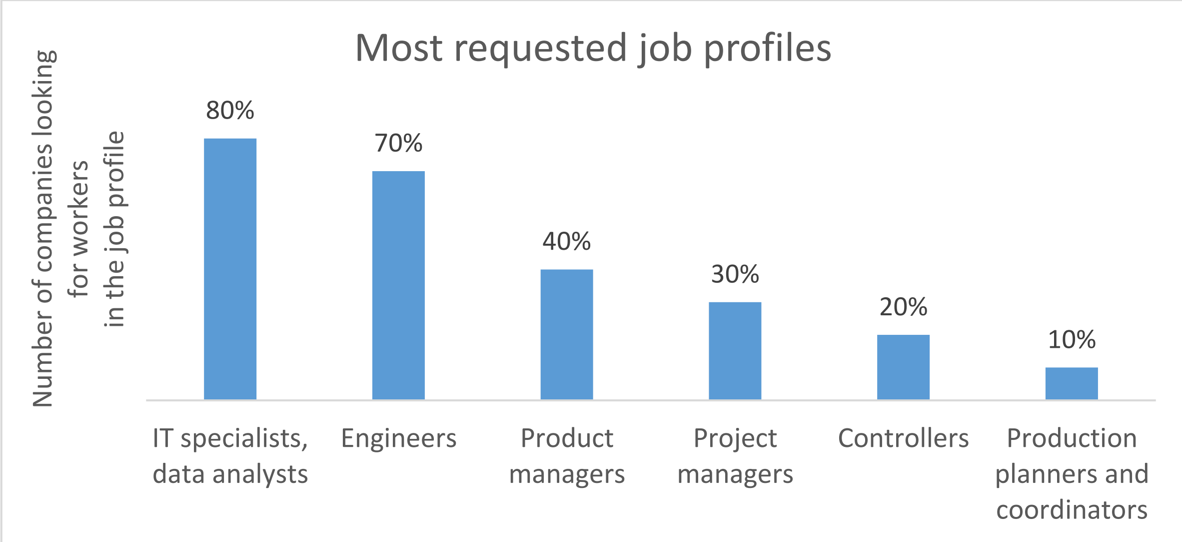

Figure 5.4 – Case study A: Most requested job profiles for Industry 4.0

A detail of the job profiles required by companies to face Industry 4.0, along with the associate job specialisation compared to the current situation is reported in Table 5.4.

Company	Job profiles	Job vertical specialisation	Job horizontal specialisation
A	Information Technology expert; Engineer within the technical function	Lower	Lower
B	Technical office manager; Automation specialist; Controller Product manager	No changes mentioned	No changes mentioned
C	Technical office manager; Mechanical engineer; Researcher with expertise in automation engineering; Software and data scientist	Lower	Lower
D	Advanced coding languages developer	Lower	Lower
E	Project manager; Automation specialist	Lower	Lower
F	Production planner; Product manager; Project manager; Controller	Lower	Higher
G	Adaptation of existing figures	Lower	Lower
H	Technical office manager; Automation specialist; Product manager	Lower	No changes mentioned
I	Key innovation users; Program Manager; Process owner engineer	Lower	Lower
J	Product and process engineer; Industrial designers	Lower	Lower

Table 5.4 – Multiple Case study A: Job profiles required for Industry 4.0 implementation

According to the results, almost all the companies are facing a workforce shortage in their companies; in some cases they are requiring additional workers for existing ones, with a generally decreasing rate of specialisation, in some others they are creating new job profiles. Only company D is trying to improve and adapt the existing employees' roles in relation to the technological innovations introduction.

The interviewed companies highlighted that, as polyvalence is becoming increasingly important in the context of Industry 4.0, new workers are no more required to be deeply specialised in a low number of activities, but they need to perform their job with proactivity and a medium level of autonomy, also involving several tasks. For instance, many interviewed companies stated that operators that previously worked on a single machine performing basic production activities, such as loading/unloading or machining operations, are now empowered and required to manage a number of unforeseen issues, which can be solved in a short time interval, thanks to the increased information content that can be accessed. Other companies mentioned a similar situation for the employees working in the logistics and warehouse fields.

Attempting to formalise the new features of work in the Industry 4.0, a new job profile typology is proposed: Autonomous Job Profiles, which refer to profiles that have higher autonomy and an enlarged number of tasks than operative ones. In terms of competences, Autonomous Job Profiles still ground on a strong presence of technical skills, but require also an increasing component of methodological skills. Starting from the job typologies defined by Spina (2012, p. 44), the Autonomous Job Profiles have been represented in Figure 5.5.

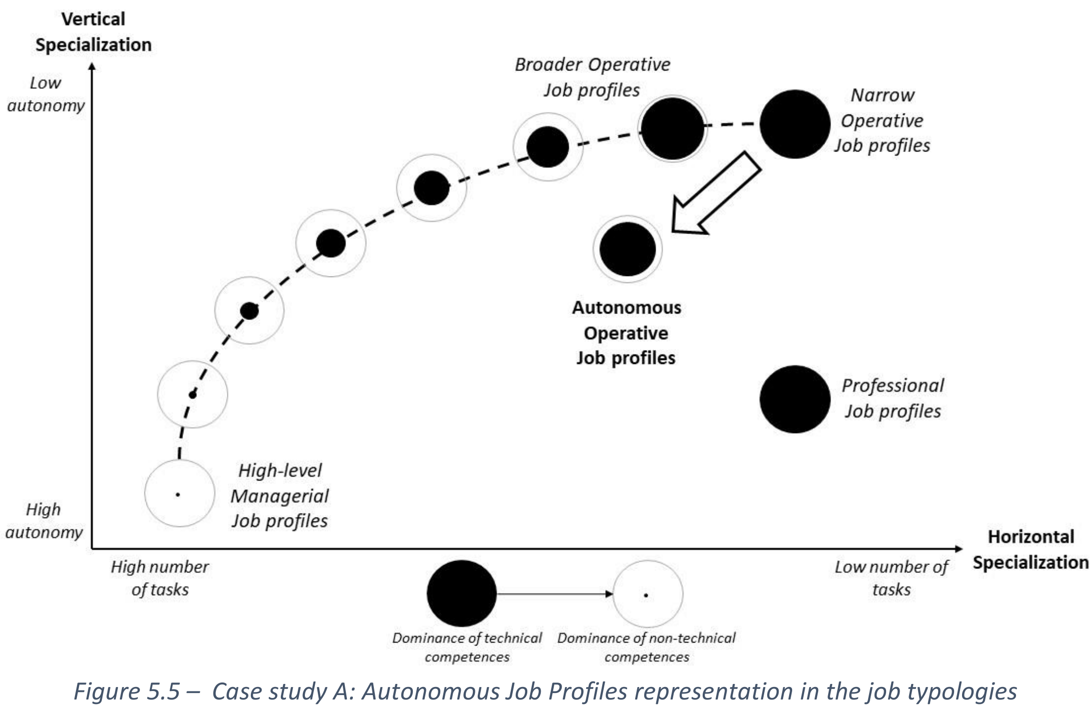

Figure 5.5 – Case study A: Autonomous Job Profiles representation in the job typologies (adapted from Spina (2012))

Organization

To assess the impacts of Industry 4.0 on organisations, finally, an analysis of the organizational chart of the case study companies has been conducted, aiming at identifying changes in the company structure in the transformation towards Industry 4.0. Among the interviewees, 50% of companies are adopting matrix organisation, with a limited number of hierarchic levels and a wide span of control, in which workers can respond to both functional and departmental managers. This is quite in contrast with the traditional functional organisation that in the past has been widely adopted by enterprises, corresponding to high-levels hierarchical structures and characterised by several levels between the chief roles and the workers, with all the business units separated and independent. Given the need of flexibility and responsiveness in the context of Industry 4.0, two of the five companies adopting matrix organisation stated that the technology introduction pushed them to change the organisational model, while the other three companies were adopting that organisational form even before, as a preparation to the technology advancement. In particular, companies that adopt a matrix organisation highlighted that there has been an erosion of hierarchical levels so that employees can perceive that the enterprise is not structured as a pyramid, but as a network, promoting more collaboration among workers. Within the other companies, which are still adopting the functional organisational structure, four of five interviewees stated that they have planned to change it towards a less-level hierarchic structure, enlarging the span of control in the middle-management job profiles. A summary of these results is shown in Figure 5.6.

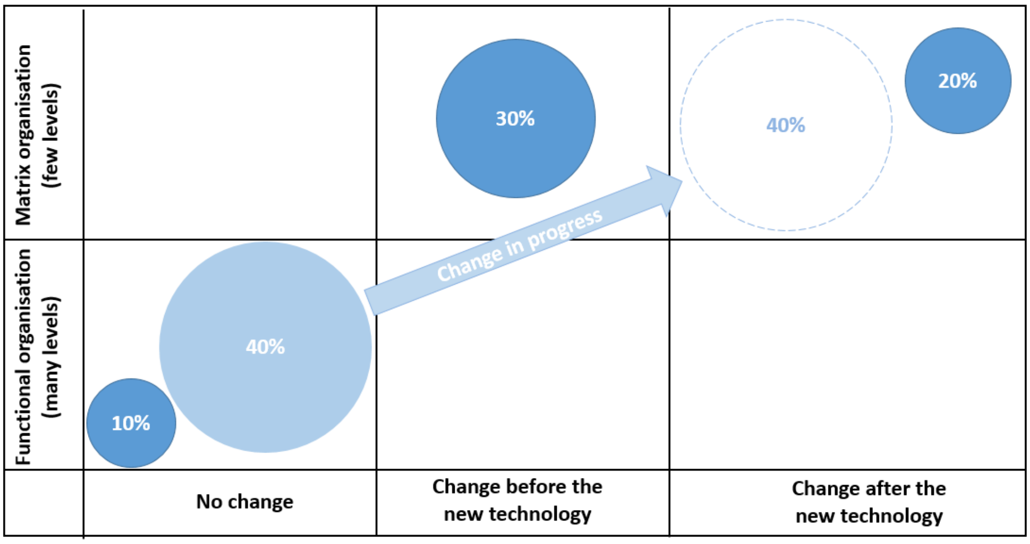

Figure 5.6 – Case study A: Organisational forms adopted by companies

The organisation structure changes have been presented by the interviewees as a natural consequence of and adaptation to the new machines, tasks and working environment. This evidences that organisational change tends to lag behind the introduction of technology, in line with one of the possible developments hypothesised in the literature (Damanpour and Evan, 1984). In fact, as previously hinted, the new emergent roles (e.g. Autonomous Job Profiles) claim for an increased decision autonomy also in some job profiles that have been characterised by low level of decision-making power in the past, such as the shopfloor operator. In addition, the task sets evolution toward more complex and cognitive activities, along with the increased availability of information and data, allow a widening of the span of control in many roles, such as the middle-management ones.

The organizational structure, the hierarchical levels, and the level of bureaucracy inside a firm are not detached from the production processes and the technological advancements. It is fundamental that firms would introduce changes also at the macro-organizational level in order to avoid problems and bottleneck situations with communication and bureaucracy difficulties.

Organizational changes, whether already in place or planned in the sample companies, display a tendency to adapt to the technological changes by introducing leaner organizational structures, characterized by a wider span of control and a reduced number of hierarchical levels, in line with what claimed in literature (Shamim et al., 2016). The empirical analysis, in fact, suggests that to go successfully in the process transformation through smart manufacturing, companies should adapt their organisational structure to allow decentralised autonomy and decision-making that support responsiveness and efficiency.

5.3. Exploring new competencies for Industry 4.0 in service companies

In the above-discussed multiple case study, the perspective of manufacturing companies that are upgrading their production process exploiting new technologies has been presented. The introduction of technology mainly affects the operational processes of the factories, which are required to become smart factories, including new connected and intelligent equipment, in order to increase the production performance of the system. Nevertheless, as introduced in Section 2.5.2 of the literature review, different opportunities are offered by Industry 4.0 to companies that are suppliers, namely technology providers or machine/equipment manufacturer, which can embed technology in their products to offer advanced product-service solutions. This kind of business transformation is referred to in literature as Digital Servitization (Bustinza et al., 2018), which represents the convergence of the process of servitization with the digitalisation promoted by Industry 4.0. As discussed in Section 2.5.2, one of the main challenges for an effective digital transformation in the servitization field is the upgrading of the workers' competences.

For this reason, also in relation to servitized companies, the exploration of the relevant competences in the Industry 4.0 context is of utmost importance. To conduct this investigation, a multiple case study approach has been used as well. It will be discussed in the following.

5.3.1. *Development of a conceptual framework*

Similar to the previous conducted multiple case study, a conceptual framework has been used as a reference point to collect data from the involved enterprises. In particular, the framework has been conceived with the aim of identifying the opportunities that Industry 4.0 brings to the servitization process in order to map the position of the companies in relation to this phenomenon. Starting from two well-established models of literature (Allmendinger and Lombreglia, 2005; Porter and Heppelmann, 2015), the model classifies the new technology-based service offerings according to two dimensions: *Smart product capabilities* and *Servitization strategies*. The model is represented in Figure 5.7, and it aims at outlining the features of the service opportunities that are created by the intersections of the two dimensions.

The x-axis represents the four servitization strategies that companies can adopt to provide smart services, supported by digital technologies, presented by Allmendinger and Lombreglia (2005). In detail:

1. *Embedded innovator* strategy represents the most product-centric perspective and consists of introducing connectivity in the product in order to get data and information useful to provide additional services.
2. *Solutionist* strategy aims at involving data collection from other activities that are performed in the whole lifecycle of the product or concern adjacencies to take advantage.
3. *Aggregator* strategy leverages on products' connectivity to network information from different sources and offers services based on a high-value body of data, making available its own device data for a third party usage (for instance, for global optimization).
4. *Synergist* strategy, similarly to Aggregator strategy, takes advantage of data from different sources to provide the functionality to other devices as well actively.

The y-axis includes the capabilities that are embedded into smart products grouped in four incremental stages, as presented in (Porter and Heppelmann, 2015):

1. *Monitoring* stage encompasses the product capabilities concerning the real-time communication of the information about its own location and condition;
2. *Control* stage includes remote control capabilities of the products;
3. *Optimisation* stage concerns the usage of algorithms and analytics able to improve and optimise product's utilization and process capabilities;
4. *Autonomy* stage refers to the advanced capabilities of products in self-coordinating with other devices, performing self-diagnosis and autonomous operations.

		Servitization strategies (based on Allmendinger & Lombreglia, 2005)			
		Product-centered		**Ecosystem-centered**	
		Embedded Innovator	**Solutionist**	**Aggregator**	**Synergist**
Smart product capabilities (based on Porter & Heppelmann, 2015)	**Monitoring**	Monitoring of product data	Monitoring of product and adjacent activities' data	Monitoring and sharing of product data in an ecosystem	Data monitoring and collection from product in the ecosystem
	Control	Remote control of product data	Remote control of product and adjacent activities' data	Product data available on cloud database	Data from product and other devices available on cloud database
	Optimization	Optimization of the product utilization	Optimization of product utilization and other activities in the lifecycle	Optimization of product utilization based on data from the ecosystem	Optimization on the whole manufacturing system
	Autonomy			Self-reconfiguration of the product	Self-reconfiguration on the whole manufacturing system

Figure 5.7 – Case study B: Digital servitization framework

The proposed framework has been verified by evaluating the possibility of filling each intersection between the two axes with service offerings already described and available in the literature. In exploring the consistency of each box, it emerged that some boxes are inconsistent by definition. For instance, *Embedded Innovator* and *Solutionist* strategies, which are focussed mainly on a single product, do not allow reaching the smart product capabilities required to achieve the *Autonomy* stage that conversely requires coordination and active communication with other devices. Actually, the two boxes that represent the above-mentioned intersections are not considered available to classify digital service offering.

The classification of service offerings according to the proposed model has the goal, similar to the technology adoption scale presented in Section 5.2.1, to identify the involvement of the enterprises in the Industry 4.0 transformation, in order to provide insights about how different levels of technology implementation can produce different competence development needs in the workforce.

5.3.2. Multiple Case study B: selection and interview protocol

To perform the case study, eight companies located in the North of Italy and operating in the machinery sector have been interviewed, in order to collect data about how they are approaching the digital servitization transformation. The companies have been selected among those one participating in the ASAP Service Management Forum, a community where scholars and practitioners from Italian universities and several leading manufacturing companies, collaborate in developing research projects and share findings in the product service management field. All the involved companies fulfil two main requirements: i) they are well-acknowledged servitized enterprises, ii) they are undertaking investments in new technologies to upgrade their service offering. The most relevant stakeholders of the companies, such as Service Directors, Human Resource Managers and CEOs, have been involved in about two-hours interviews, which has been done face-to-face by two researchers and has been recorded in order to increase the internal reliability of the study (Yin, 2009). The details of the company demographics is summarised in Table 5.5, while the interview protocol is reported in Appendix C.

Company	Location	Turnover	Employees	Main product offering
A	Brescia	> 100 M €	>200	Forklift and earth moving machines
B	Brescia	> 100 M €	>200	Solutions for textile
C	Bergamo	< 50 M €	<100	Assembly machines
D	Milano	50÷100 M €	>200	Machine tools
E	Brescia	< 50 M €	>200	Energy machines
F	Torino	< 50 M €	<100	Sensors and identification solutions
G	Bergamo	> 100 M €	>200	Machines for chemical industry
H	Bergamo	> 100 M €	>200	CNC machines

Table 5.5 – Multiple Case study B: Company demographics

Thanks to the support of ASAP in conducting the case study, it has been possible to collect data about the degree of digitalisation of current service offerings and the future trajectories of digital service development. Along with this, based on the same competence framework used in the previous case study (see Section 5.2.1), provided by Hecklau et al. (2016), the competences that companies are envisioning as the most relevant in relation to their digital transformation journey have been analysed.

A summary of the case study research is reported in Table 5.6.

Who conducted the case study?	Each case study involved at least two researchers to achieve reliability and validity
What are the methods used to conduct the case study?	Interviews
When did interviews take place?	In 2019
How many companies have been involved?	8 companies
What was the aim of the interviews?	Investigate the phenomenon of digital servitization inside the companies to bring out:

	• The impact of the new technology adoption on the competences required to workers • The gap between the identified relevant competences and the already present competences in the company
What were the topic addressed in the interviews?	• General data about company business (e.g. dimension, workers, customers) • The relevance of servitization and digitalization trends for the company • Industry 4.0 Technologies adopted in products/processes • Impacts of technologies on competences

Table 5.6 – Case study B: Summary

5.3.3. Multiple Case study B: results

Digital servitization paths

Based on the analysis of the current and future product-service offerings of the case studies companies (which are reported in Appendix D), the trajectories of the companies' transformation toward the digital servitization have been envisioned and are represented in Figure 5.8. Analysing the starting points of the depicted paths, it emerges clearly that most of the companies are currently adopting strong product-centred strategies, namely *Embedded Innovator* and *Solutionist*. This is related to the fact that companies are mostly offering standard services, such as maintenance, to support their customer in the usage of their products, which are mainly machines and production equipment. However, also in the present state, they are adopting technology at different levels: six companies are already offering remote control of products data, while two companies are even exploring optimisation capabilities in their products. In the first case, remote monitoring and control allow the possibility to offer improved standard services as reports of the product data and provide new simple tools for extracting functioning data from the machines, which can be used later autonomously by their customers for further analysis. In the second case, among the machines manufacturers, company B already reaches the *Optimisation* capability, including artificial intelligence and data mining algorithms in their products to provide predictive maintenance, while company F, which is a supplier of technological solutions for the machinery industry, provides customers with data analysis tools, that are developed internally by a new team in the quality and service departments in charge of the data management.

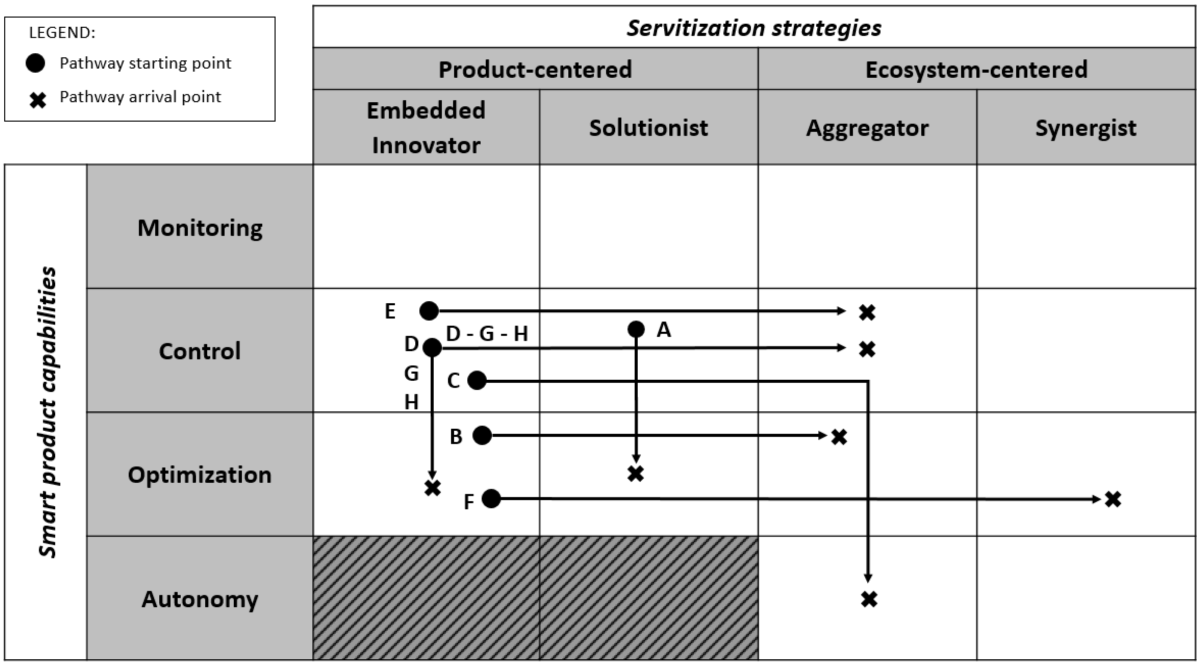

Figure 5.8 – Multiple Case study B: Digital servitization paths

Looking at the depicted paths, moreover, it is possible to highlight two principal directions that companies are undertaking. About all the companies are moving to the *Aggregator* and, only in a case, toward the *Synergist* strategies, creating infrastructures and cloud platforms supporting the data collection, sharing and visualisation and enabling the integration of data from their products with other data sources. On the other hand, companies like A, C, D, G, H, are moving to the *Optimisation* capabilities of products, improving their knowledge in the data analysis area to provide predictive maintenance tools and advanced data analytics for improved decision-making to customers. Some companies are combining the two directions (e.g. company C) or they are moving in parallel in the two (e.g. D, G, H) as well. Only company C is working to develop self-configuring potentialities in their assembly lines and reach the *Autonomy* capability. In this case, data collected from machines, equipment and products that are manufactured will be used to reconfigure the line stations and perform self-diagnostics, aiming at preventing faults and stops in the production, which would generate huge time and productivity losses.

Analysing the depicted paths and the arrival points, finally, it is possible to state that almost all the companies recognise the value of shifting from a product-centred to an ecosystem-centred approach (horizontal paths) and, in particular, the *Aggregator* strategy seems to be the main strategy that companies are wishing to achieve. Only company F aims at becoming a *Synergist*, offering data analysis and optimization for other stakeholders and partners, through an extensive data collection from several devices.

As a result, the two highest levels both in x-axis – *Synergist* strategy – and y-axis – *Autonomy* level – are rarely envisioned as arrival points for the digital servitization transformation by the enterprises. Companies are often satisfied when reaching lower levels of technological capability and limited interaction with external devices, adopting technological solutions that guarantee a more straightforward implementation. In fact, introducing Industry 4.0-based services poses both challenges related to the servitization journey (Alghisi and Saccani, 2015) and barriers related to Industry 4.0 technologies implementation (Khan and Turowski, 2016). In particular, the complexity in transferring the value of services to customers is emphasized in the case of digital services, which are even less tangible.

In addition, relevant issues in shifting from a product-centred to an ecosystem-centred culture are the privacy and property of data, the standardisation of information sharing procedures, while the *Autonomy* level requires the development proper infrastructure and the introduction of several new technologies, which requires consistent investment and dedicated technicians to implement and maintain them.

<u>Competences</u>

Based on the model presented by Hecklau et al. (2016) that has been used also in case study A, the data collected from the interviewed companies were coded and analysed. The competences identified as relevant to move towards the digital servitization transformation by companies have been reported in Appendix E. From a quantitative analysis on the mentioned competences, it has been figured out how technical and methodological competences are envisioned as most relevant, compared to the social and personal ones. In a first analysis, the relevance of the four competence categories has been assessed calculating the percentage of competences for each category on the total set of competences selected by each company and the average value of these percentages over the eight companies. The results are represented in the second column of Table 5.7. In the second analysis (reported in the third column), the percentage of competences selected by companies for each category on the total number of competences included in each category of the model of Hecklau et al. (2016) have been calculated, providing a rate of importance for each category. Given the fact that the four categories include different numbers of competences, these percentages have been normalised to make a comparison among the categories. The average percentage has been finally calculated as the mean over the eight companies.

The same results are shown in Figure 5.9 as ranges of importance for each category, using the values included in Table 5.7.

Competence category	Category Relevance (Analysis 1)	Category Relevance (Analysis 2)
Technical Competences	31,7%	36,5%
Methodological Competences	32,2%	27,9%
Personal Competences	14,8%	17,1%
Interpersonal Competences	21,3%	18,5%
Total	100 %	100 %

Table 5.7 – Multiple Case study B: Competence analysis

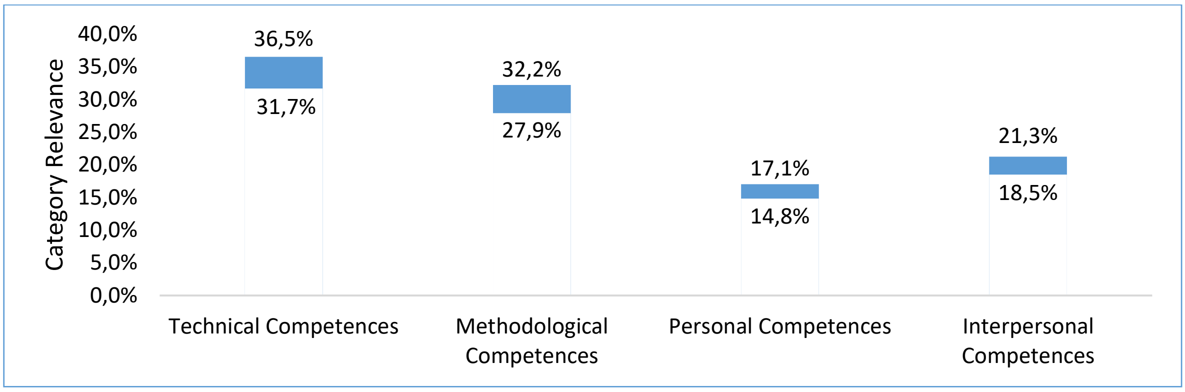

Figure 5.9 – Multiple Case study B: Competences analysis (range representation)

According to the companies' interviews, having comprehensive technical skills and being acknowledged and able to code is fundamental for the employees. Also understanding the IT security turned out to be critical as well. Among methodological competences, capability to structure and examine large amounts of data, manage complex processes and solve problems in an efficient way are the most relevant aspects. From the personal competences point of view, it emerges that being flexible and able to work under pressure are of utmost importance in the changing market environment. Finally, interpersonal competences such as communication skills, compromising, cooperation and leadership, have been mentioned as most important to improve the customers' relationships.

Combining the competences analysis with the digital servitization paths before identified, it is possible to notice that companies, such as C, D, E, which are *Embedded Innovators* and aim at improving product capabilities toward optimisation and autonomy, demonstrate an important gap in the relevance of technical/methodological competences compared to personal and interpersonal ones. Despite a similar digital servitization path, company G identifies as relevant many competences also in the area of personal and interpersonal ones, suggesting that difference between companies' cultures and ways of approaching the digital servitization influences the competence development.

Company F that aims at becoming a *Synergist* shows a good balance among the four categories of competences as well, highlighting the importance of developing soft social skills such as the ability to work in team and leadership when creating an ecosystem of collaborative platforms.

Moreover, it emerges that the presence of the different categories of competences, in the different case studies, depends mainly on their digital servitization strategy. Moving from a product-centred towards an ecosystem-centred company demands the development of soft skills, specifically personal and soft while adopting digital technologies demands advanced technical and methodological skills.

As discussed in the previous section, companies seem to be held back in proposing new Industry 4.0 technology-based services, in relation to the challenges that they have to face. The competence development is undoubtedly one of the major issues, considering that not only technical skills but also methodological, personal and interpersonal ones play a crucial role.

5.4. RQ2 Outcome

This chapter aimed at answering to RQ2:

> **What are the competences required by introducing new work attributes that exploit Industry 4.0 technologies?**

The investigations carried out through two multiple case studies aimed at analysing the impacts of the introduction of Industry 4.0 technologies on the job profiles and competences required to workers, referring to both the two interfaces Technology-Organisation and Human-Organisation of the HTO model. The two multiple case studies provide empirical evidence about the existing interconnection between technology implementation and work changes. The development and outcome of RQ2 is depicted in Figure 5.10

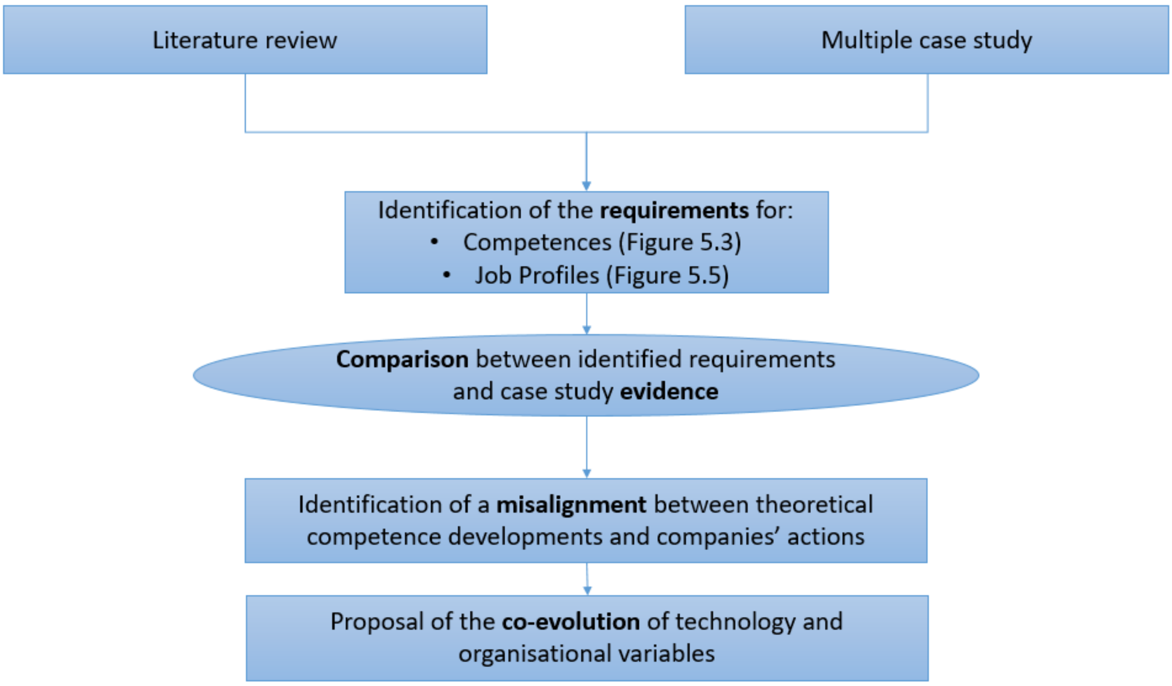

Figure 5.10 – RQ2 development and outcome

In particular, from the literature review and the case study analysis, it has been pointed out that Industry 4.0 technologies are affecting the nature of work requiring job profiles characterised by a medium level of vertical and horizontal specialisation. Autonomous Job Profiles have been presented as a new typology of job profiles able to support the Industry 4.0 transformation, thanks to the increasing autonomy and the larger number of tasks conferred to workers. Technical job profiles seem to be the most relevant to promote technological innovation, but also middle-management profiles in the field of project management and production planning are gaining importance.

Strictly related to this, the competence analysis demonstrates how technical competences, and in particular those ones related to IT, automation and data analysis, are of utmost relevance for the companies, that are pursuing different training strategies to develop them. Nevertheless, it has been discussed how to reach maturity stages in the technology adoption, that is to integrate technology efficiently in the company processes, a right combination of technical and soft skills is required. Methodological competences, such as problem-solving and analytical skills, have been envisioned as the most relevant among soft skills and this is aligned with the request of job profiles, such as data analysts and project managers, in which methodological approaches play a fundamental role.

Personal and interpersonal competences are not perceived as important as the previous mentioned, but they are needed in the last stages of technology adoption, in order to manage properly several stakeholders, both for manufacturers improving their production processes toward horizontal and vertical integration, and for service providers aiming at creating shared platforms with customers.

According to the results of the two multiple case studies, it emerges that currently companies are developing mainly technical skills, lacking in many cases social and personal competences development. Moreover, it occurs often that companies introduce new technical roles to support the implementation of technological innovation and do not care about training people also from a methodological and operational process point of view. Commonly, soft skills are underestimated and taken for granted by companies and the result is that they are not developed properly. On the contrary, to complete technical hard skills, soft skills are recognized to be essential (Cotet et al., 2017).

The gaps between theoretical competence development and real actions undertaken by companies could be critical for an effective transformation toward Industry 4.0 and require serious reflexions. As discussed in Section 5.2.3, to reach the highest level in technology adoption, namely to exploit the potentials of digital technologies at most, a right combination of technical, methodological, personal and social skills should be implemented. Asynchronous development of hard (i.e. technical) and soft skills can lead in the long term to poor results in transforming the company processes (both for production activities and service processes) into fully integrated and efficient ones.

A holistic competence development also supports the need of the enterprises to create new roles that have a medium level of vertical and horizontal specialisation (i.e. the previously mentioned Autonomous Job Profiles), given that not only deep technical skills are required, but also methodological skills to manage complex processes with autonomy and flexibility. Similarly, personal and interpersonal competences play a crucial role to support the decentralisation and the leaner organisation structures that companies are adopting to be responsive and effective. In fact, as collaborative business processes and operating models characterise the shift to the Industry 4.0 paradigm (see Section 2.5.1), the importance of managing teams and multiple stakeholders is extremely important and require well-developed communication and negotiation skills.

In addition, this chapter aimed at discussing how organisations and technologies need to co-evolve. A common mistake that companies often make (and, indeed, I4.0 technologies are no exception) is assuming that technological investments (e.g. acquiring a new machine) will automatically generate a positive impact on performances and that the organization should adapt to the technological solution. Conversely, technologies should not guide the redesign of the organisation, but companies should leverage on them to make the organisation capable of adapting to new processes.

Unfortunately, in many cases, companies underestimate the cost and difficulties of introducing new technical solutions in an organised system. The design of a structured process and a clear set of tools to favour the organizational development are of extreme importance to provide a plan of development of the enterprises. That is the reason for which the joint analysis of Human-Technology-Organisation perspectives is relevant to manage properly the Industry 4.0 transformation.

5.4.1. Relationship between RQ2 outcome and the other RQs

Concerning the general thesis objectives, the RQ2 relates to both the perspectives of Human-Organisation and Technology-Organisation interfaces of the HTO model (see Figure 3.1). In particular, starting from the results of RQ1, the case study research presented in this chapter, investigated what are the new competences that workers need to develop to comply with the new tasks they are assigned to. The increasing amount of cognitive and non-routine tasks is coherent with the results of RQ2 that deem as convenient a well-balanced development of technical and non-technical skill. Moreover, the technology adoption and the increasing human-technology interaction impacts on the work organisation and claims for a changing paradigm in the job profiles too, introducing more autonomous and polyvalent figures, in contrast to specialised profiles.

Indeed, the combined results of RQ1 and RQ2 cover all the interfaces of the HTO model and will be used in the RQ3 as necessary steps to design the role of humans in the smart factories and in the roadmap for the industrial implementation of the next generation manufacturing systems.

6. THE HUMAN-TECHNOLOGY INTEGRATION IN THE SMART FACTORY

The previous chapters highlighted how the human work will change and evolve towards a new paradigm in relation to the Industry 4.0 technological innovations.

As dealt with in previous chapters, the role of technology in the organisations has been addressed from several perspectives in the literature. In the body of work including (Leavitt, 1965) (See section 5.2.1) the focus was on the impacts of technology on organisational variables such as structure, jobs, etc. The works of Socio-Technical Systems theorists and other scholars, conversely, focussed on the human power and decision in using and controlling technology (e.g., Trist et al., 1963). Attempting to merge all these perspectives, Orlikowski (1992) proposed a model in which the technology has a dual role, namely it is enacted by humans agency but it is also institutionalised in structure.

This approach supports the aim of this section, that is encompassing all the previously discussed aspects about the impacts of technology on the human work, finally providing a more general view of the role of humans in the next generation manufacturing systems, namely in the smart factories. According to the HTO model, this third section includes all the three elements of human technology and organisation, addressing the topics of i) the interaction between humans and intelligent manufacturing equipment (e.g., smart machines) and ii) the involvement of humans in the intelligent orchestration of the manufacturing environment. To address these aspects, it is crucial to understand the possible ways of interaction of the smart factory elements envisioning appropriate organisational and control models. It is also essential to understand what roles humans can play in such a scenario.

Indeed, many manufacturing systems are human-centred, and human operators are required to interact with intelligent devices all around. Literature offers valuable contributions in this field, under the stream of research concerning Human-In-The-Loop (Sousa Nunes et al., 2015). However, the new Industry 4.0 paradigm imposes a deeper reflection on the modes of interaction not only between humans and machines, but also in relation to the other smart objects which coexist, such as products, transport systems, and so on. To address this topic, the concept of Human-in-the-Loop Cyber-Physical Production System (HITLCPPS) will be presented along with a discussion about the roles that human operators can play in such a system. Then, the interaction of several typologies of HITLCPPS is explored, discussing the evolutionary role of communication and control architectures that can be applied to regulate the decision-making processes in a factory. The focus on the human centricity in the manufacturing systems finally results in a scenario of a Social Human-in-the-Loop Cyber-Physical Production System, in which many agents collaborate and are socially connected both at the physical and cyber levels. To develop such a scenario, in the final part of this chapter, a socio-technical roadmap is proposed.

6.1. The smart factory as a socio-technical system

As introduced in Section 2.3, currently, the Industry 4.0 vision is mainly reflected in the concept and development of smart factories, which represent the archetype of the next generation production systems, also referred to as Smart Manufacturing Systems (SMS) (Kusiak, 2018) and Cyber-Physical Production Systems (CPPS) (Monostori, 2014). Interactions between humans and machines in smart factories, often referred to as socio-technical interactions, take place continuously; therefore, proper conceptual socio-technical models should be considered to gain a complete understanding of this complex system (Bücker et al., 2016). A detailed explanation of the socio-technical nature of the smart factory environment has been included in Section 2.6.

Many technologies can be implemented in a factory to move towards the Industry 4.0 concept and their orchestration is fundamental for the development of manufacturing processes that are defined as "smart". According to Kusiak (2018), a smart manufacturing enterprise is structured in two layers, the physical one and the cyber one, which are linked by an interface. The same vision is represented in Yao et al. (2017) under the label of Cyber-Physical Production System (Figure 6.1).

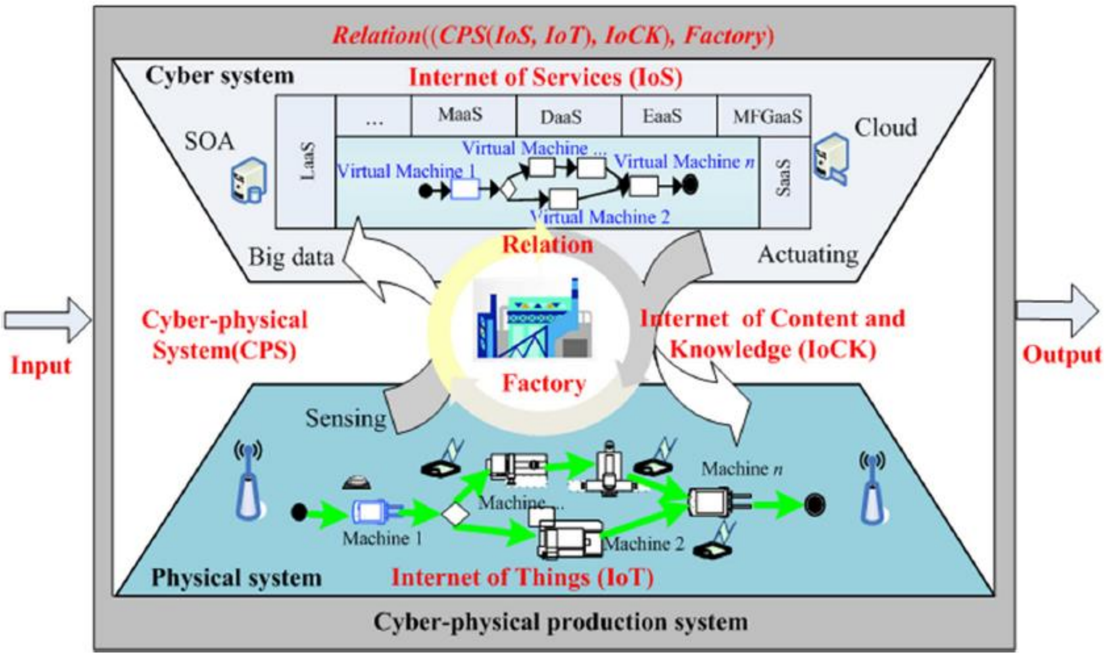

Figure 6.1 – Main elements of a Cyber-Physical Production System (Yao et al., 2017)

In this sense, smart manufacturing grounds on the CPS theory, which postulates the connection of physical entities with digital counterparts that represent them in the cyber space (Oztemel and Gursev, 2018). Moreover, the terms "Smart Manufacturing Systems" (SMS) and "Cyber-Physical Production Systems" (CPPS) are often used interchangeably to refer to smart factory processes characterised by real-time data access capability, reconfigurability, decentralised decision-making and intelligence (Yao et al., 2017). In literature, the integration of human capabilities with CPS resulted in the definition of the concept of Human-Cyber-Physical System, referred as a "systems engineered to (a) improve human abilities to dynamically interact with machines in the cyber- and physical- worlds by means of 'intelligent' human-machine interfaces, using human-computer interaction techniques designed to fit the operators' cognitive and physical needs, and (b) improve human physical-, sensing- and cognitive capabilities, by means of various enriched and enhanced technologies (e.g. using wearable devices) (Romero, Bernus, et al., 2016).

Enlarging the vision from a single CPS to a CPPS (or a smart factory), it appears that several smart manufacturing processes coexist and require proper communication interfaces and infrastructure, in order to create a real-time integrated network. In CPPS, data from the physical equipment is sent to the cyber space to be elaborated. Conversely, decisions are pushed down from the cyber to the physical layer. Nevertheless, intelligence is both at the central and distributed level, enabling responsiveness through decentralisation and, at the same time, wide-awareness at system level (Kusiak, 2018).

6.1.1. Modelling Smart Manufacturing Systems with agents

To deal with the complexity of a smart manufacturing environment, new organisational forms and production control architectures are required to manage the emerging hybrid scenario where humans and CPS cooperate to deliver outputs. The concept of multi-agent systems is a well-suitable approach to model and control smart manufacturing systems (Premm and Kirn, 2015). Since an agent is "an autonomous component that represents physical or logical objects in the system, capable to act in order to achieve its goals, and being able to interact with other agents, when it does not possess knowledge and skills to reach alone its objectives" (Leitão, 2009), a smart factory can be compared to a multi-agent system (MAS), that is an organised set of agents. In S. Wang et al. (2016), smart shop-floor objects are modelled as agents, which cooperate through intelligent mechanisms to reconfigure dynamically a production system. These objects are machines, conveyors, and products. Actually, according to literature, the main features of agents are autonomy, reactivity, pro-activity, social ability, cooperation, organisation, rationality, learning and mobility (Giret and Botti, 2004). The same characteristics are associated with holons, which are autonomous and cooperating conceptual entities that can represent a physical or logical object/activity (Leitão, 2009). In the past, agent-based and holonic manufacturing systems (HMS) have been conceived to model decentralised and distributed intelligence in manufacturing control. Both MAS and HMS are considered roots of CPPS (Monostori, 2014), and are still suitable concepts to model the control architectures of Smart Manufacturing Systems (Jones et al., 2018). Despite few differences, the agents and holonic paradigms share similar concepts and basically have the same properties (Giret and Botti, 2004). Therefore, the terms agent and holon will be used as synonyms in this research. These architectures enable a dynamic adaptation and reactivity against production uncertainties (Cardin et al., 2017), which are necessary requirements of SMS. Reactive control systems, in fact, highly support the productivity and flexibility of a manufacturing system (Cavalieri et al., 2003). A detailed description of relevant agent characteristics supporting specific CPS aspects is reported in (Leitao et al., 2016).

A framework for agents technology applied to Industry 4.0 is proposed in Adeyeri et al. (2015) and reported in Figure 6.2. In this framework, the information flow among agents is enabled by wireless technologies to realise a reconfigurable manufacturing system. Nevertheless, the human factor is not identified by a specific agent, and the interaction between human and technology is not depicted.

As distributed intelligence solutions usually implemented in MAS and HMS architectures enable to complement the human skills in the management and control of production processes, the integration of humans in such systems, also referred as human-in-the-loop (HITL), is an important issue in the development of CPSs (Leitao et al., 2016). Different opportunities for designing the role of human-in-the-loop are recognised and discussed in the following section.

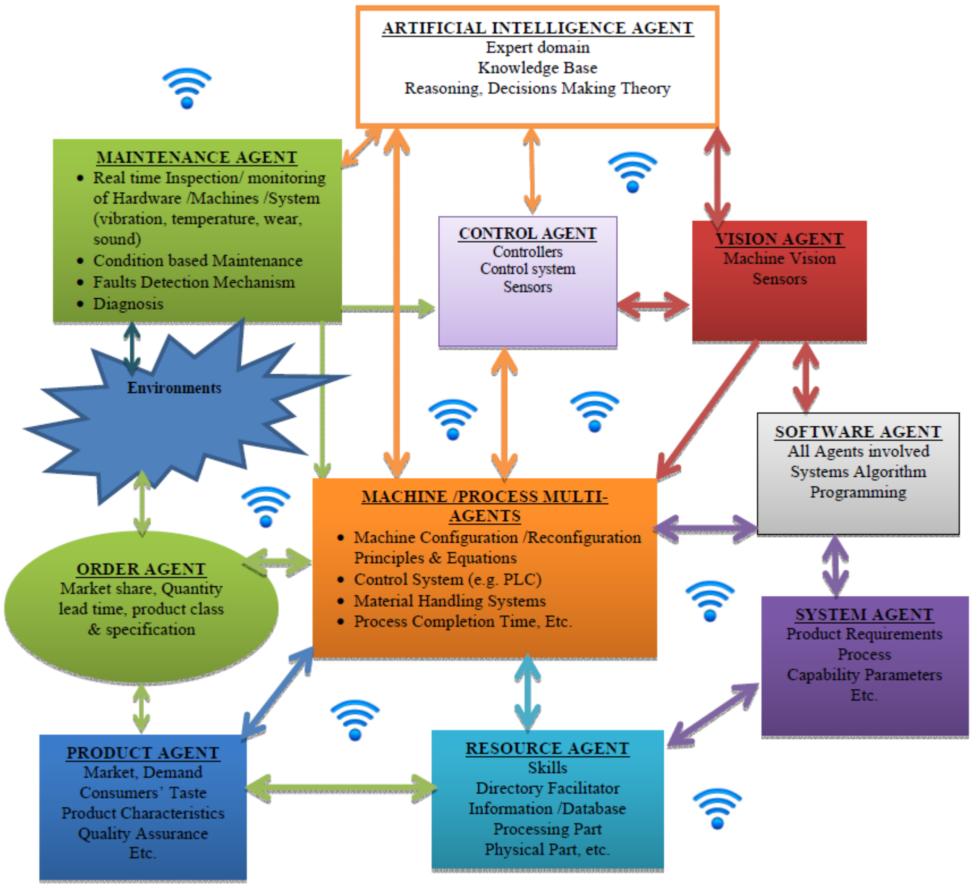

Figure 6.2 – A Framework of agent technology for Industry 4.0 (Adeyeri et al., 2015)

6.2. Human agents in CPPS

For many years, manufacturing systems based on multi-agent and holonic technologies have been designed with a “techno-centric” approach, considering the human operator as an external supervisor devoted to manage unforeseen situations and issues and support the intelligent control of the manufacturing system (Pacaux-Lemoine et al., 2017). Control algorithms and systems that include actions performed by humans, represented by transfer functions in block diagrams, are commonly named as Human-in-the-loop control problems (Hess, 1999). In most of these systems, human intervention is invoked only to solve problematic situations that arise, contributing to the idea of a “magic human” able to always perform the right decision (Pacaux-Lemoine et al., 2017). Conversely, in cyber-physical production processes it is essential to consider the human presence and behaviour as a key inclusive part of the system, instead of an external factor (Sousa Nunes et al., 2015).

To explore this changing paradigm, it is necessary at first to explore the different contributions that humans can give to a smart factory. For this purpose, in Nunes et al. (2017) a taxonomy of the human roles in Human-In-The-Loop Cyber-Physical Production Systems (HITLCPPS) is presented. Starting from this taxonomy, a revised proposal has been elaborated and represented in Figure 6.3.

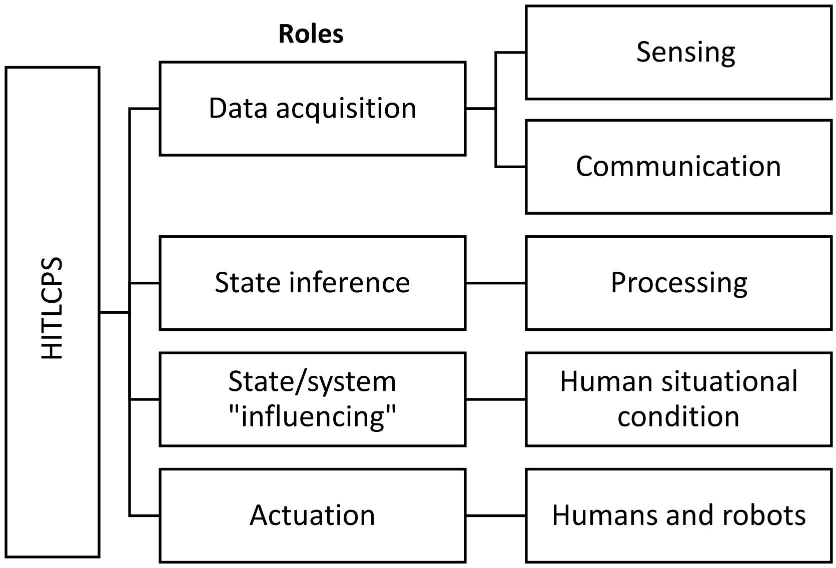

Figure 6.3 – Taxonomy of human roles in HITLCPPS (Adapted from Nunes et al. 2017)

Four main roles humans can assume:

- *Data acquisition.* The capacity of humans to capture data and information makes it possible to assume them as sensors, able to feed the system with additional sources. For instance, the operators in the shop floor can provide the information systems with complex information about failures, which are difficult to detect with sensors. Indirect sensing can be achieved also using wearable devices that gather data from the environment where the human is immersed, such as the temperature, humidity and light intensity of the production plant.

- *State inference*. Humans can directly provide additional data processing and computational capability to a system thanks to their cognition and mobile devices they are equipped with. In the first case, the cognitive capabilities of humans (e.g. memory, calculation, and reasoning) directly allow data elaboration that supports, for instance, decisions about maintenance strategies, production control, logistics activities and so on.
- *State/system "influencing"*. Given the possibilities to retrieve data from humans about their physical and psychological state, CPPS can adapt and modulate their functioning according to human needs, for instance for ensuring health and safety against possible dangers.
- *Actuation*. Human actions still have extreme importance in the management of CPPS. In particular, human and machine actuation need to co-exist and be properly integrated, complementary or even collaborative. Humans actuate decisions through both manual operations and direct control of the production devices using Human-Machine Interfaces.

The potential of HITLCPPS is not related only to the contribution that humans provide to the system, but also to the augmentation of human capabilities thanks to the introduction of the key enabling technologies characterising a smart factory, as previously discussed in Section 4.3. To match these two concepts, a matrix linking the enabling technologies with the role of humans in a HITLCPPS is provided in Table 6.1. In this table, Cybersecurity is not considered. being the body of knowledge that encompasses technologies, processes and practices designed to protect cyber space from attacks and damages (Möller, 2016), cybersecurity does not support the integration of humans in CPPS, but it provides information security in all the smart factory network.

HUMAN ROLES	**Data acquisition**		**State inference**	**State influencing**	**Actuation**
	Sensing	**Communication**	**Processing**	**Human situational condition**	**Humans and robots**
Physical	• Augmented reality • Virtual reality			• Advanced robotics	• Advanced robotics • Additive manufacturing/ 3D printing
Cognitive		• IoT • Cloud technol-ogies	• Cyber-physical system • Simulation • Big data analytics • Horizontal and vertical integra-tion • Multi-agent tech-nologies • Energy saving technologies	• Smart sensors • Cyber-physical system	

Table 6.1 – Enabling technologies for human support in HITLCPPS

From the table, it emerges that technologies supporting the physical capabilities of humans are particularly useful to enhance the sensing and actuation role of human operators. For instance, augmented reality improves the visual sensing capability of the maintenance operators enabling to add virtual objects and information to the real space to perform better repair operations. On the other hand, communication skills and inference capacity are upgraded by many cognitive technologies, which augment human capabilities in processing and sharing information in a HITLCPPS. For example, big data analytics supports the elaboration of technical data collected by the machines to enable predictive maintenance while simulation allows the evaluation of different production plans to guide the choice of the better production planning strategy. Finally, state influencing interaction can take advantage of both physical and cognitive technologies. For instance, advanced and collaborative robots, which cooperate with the operator in production activities, are able to detect the human position and movement and arrange their behaviour accordingly. In this way, the human situational condition affects the state of the production system. In addition, cognitive technologies, such as smart sensors, are able to monitor human health condition through data collection from wearable (e.g., smart watches) and fixed systems (e.g., cameras). For instance, according to a fast data elaboration, when the operator health status is downgrading due to fatigue, smart sensors can provide information to the system that can change its state (e.g., production rhythm) to avoid possible accidents and damages for the operator.

6.3.Social Human-In-The-Loop Cyber-Physical Production Systems

6.3.1. Human-machine interaction in HITLCPPS

The previous paragraph highlighted how Industry 4.0 technologies affect human roles in a smart factory. Now, the focus shifts to understanding how next generation production systems should be shaped to benefit from these new roles.

Analysing a single human-machine interaction, it is possible to recognise different approaches. In typical HITL scenarios, human operators usually monitor and control machines through interfaces designed to display data and information, and to enable direct human control on the machine (Lee and Lee, 2016). To accomplish this task, Human-Machine Interfaces (HMI) often refer to physical devices or control panels mounted on production equipment. The proper design of HMI is a deep-investigated research topic both at the theoretical and practical level. However, the attractive design of HMI for enhancing human performances in CPPS through better adaptable and intuitive interfaces is still recognised as one of the main fields of research and action (Stern and Becker, 2017). It is possible to model such a human-machine system with holonic architectures as well. In this case, the HMI is represented by an interface holon (or an interface agent), which interacts both with a human worker and the machine system, controlling the information exchange between them (Leuvennink et al., 2019).

A second approach to describe human interaction with machines has been researched under the term of Joint Cognitive Systems (JCS). In this case, humans and machines are no longer separated entities collaborating through an interface; instead, they execute tasks as a team. Main features of Joint Cognitive Systems are goal-orientation, control, and co-agency, defined as the working together of humans and machines (Hollnagel and Woods, 2005; Jones et al., 2018). Using the holonic architecture view, the human worker is now modelled as a holon embedding the interface needed to communicate with machines (Leuvennink et al., 2019). Within this approach, the holonic manufacturing system can have direct joint control over human and machines resources, with consequent enhanced flexibility and responsiveness. Joint Cognitive Systems aim at overcoming the need of awaiting direct actions on the system from a human agent in charge of decision-making but implies a collaborative scenario, in which continuous interaction and data exchange between humans and machines occurs. Moreover, all material and immaterial holons (such as machines, products, but also production orders) become parts of an assistance system that help humans enhance performance (Pacaux-Lemoine et al., 2017).

Although these two approaches are useful to describe a single human-machine interaction, a smart factory can be viewed as a network of agents that cooperate to perform a various combination of physical and cognitive tasks (Jones et al., 2018). This suggests that further investigations have to be conducted to have a wider perspective. In fact, in a smart factory many human agents can interact with a plethora of other agents, such as machines, products, software, artificial intelligence tools, etc. The objective of these interactions is to provide the system with the right decisions to control the manufacturing process, ensuring high performance and productivity. Therefore, a Human-in-the-Loop control system, as described so far, is only a cell of a more complex system. Beyond the human-machine interaction, social interaction among smart factory agents needs to be modelled.

As suggested by the HTO model, besides the interaction between human and technology, the human-organisation and the technology-organisation relationships are of utmost importance. In a SMS, the organisation subsystem is in charge of the coordination of both human work and technological capabilities of the system and includes all the social interactions and control mechanisms of a factory. In this field, it is possible to formalise different ways of organising the manufacturing processes and recognise an evolution of their control towards the smart factory paradigm. The steps of this evolution are represented as scenarios in Figure 6.4. In each scenario, according to the previous discussion about the different possibilities in designing human-machine interaction, the human-machine cell is the single unit of analysis, and the interactions among these units are discussed. For the sake of simplicity, three units are depicted to represent a factory, being aware that in a real manufacturing process they might be more.

Scenario #1 represents a simple case in which humans collaborate and share information through direct communication among them. This kind of interaction is not supported by digital systems, as it usually occurs verbally. In this scenario, each operator can only have a partial view of the production system, which is strictly related to the machine that he is controlling. Machines do not have any capability in terms of communication. For these reasons, the control of this system can be particularly complex and suboptimal, because a limited view on the process means limited awareness about the whole system and does not allow humans to take optimal decisions. Traditionally, in the past, simple production systems, such as mechanical workshops, adopted this scenario to control the production.

In Scenario#2, a modest evolution is represented by the introduction of digital support (e.g., ICT tools) for human-to-human communication. Also in this case, machines can not communicate with each other, and humans have a partial view of the system; however, the introduction of stand-alone information systems allows the development of more complete Decision Information Packages (DIP) (Hoos et al., 2017), that are the sets of information relevant for the operators for taking decisions. Nevertheless, the control of the manufacturing process is decentralised, and data that compose the DIP reside in many systems that are not integrated, making it difficult to perform optimal process control actions. In real factories, this scenario is represented by production systems that adopt some departmental information systems which support independently different areas, such as internal logistics and warehouses, production plans, products information.

In both scenarios #1 and #2 manufacturing control is organized according to a heterarchical architecture, in which independent agents have local intelligence and cooperate through negotiation mechanisms to achieve their goals (Van Brussel et al., 1998). In the represented scenarios, human-machine cells represent single agents, that can arrange their work locally, and humans have a direct control on the machines they are working with. The drawback of this approach is that it is not possible to use global information for managing all the human-machine systems present in a factory. Only single interactions between two human-machine systems are allowed, while multiple interactions are not possible. On the other hand, Scenario #3 represents a common control architecture for manufacturing processes in the era of ICT and automation. A central information system manages data sharing and communications among humans.

For instance, this is the case of Enterprise Resource Planning (ERP) and Manufacturing Execution System (MES), which collect and organise the information of the whole enterprise, to control the production and other related activities (e.g., materials flows, human resources, cash flows, etc.). In this scenario, centralised and hierarchical control structures can provide a good capability of optimisation and productivity (Leitão, 2009). However, also in this case, several issues arise: centralised systems have slower speed of response with respect to decentralised systems, due to the high quantity of work in charge of the central system in managing huge numbers of agents. In hierarchical architectures, problems in responding to real-time events can be caused by limited local intelligence combined with a short-sighted view of the high levels towards detailed information from the shop floor; these issues become more evident if the communication links between levels are not reliable (Dilts et al., 1991). For these reasons, agility and flexibility of such systems can not be guaranteed.

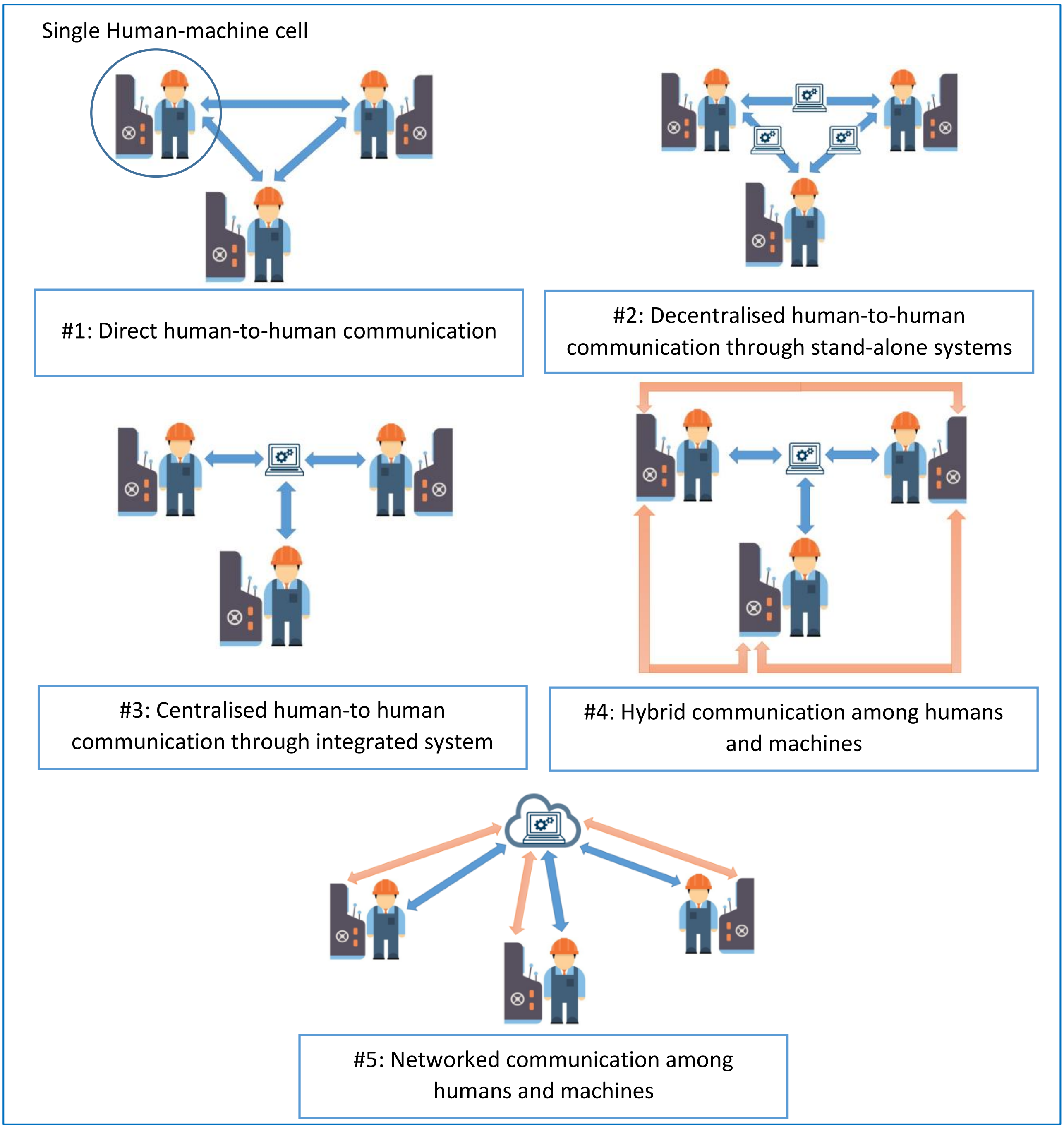

Figure 6.4 – Social Human in the Loop Cyber-Physical Production Systems scenarios

Aiming at overcoming all the problems of both centralised and decentralised control problems, hybrid control solutions have been conceived and proposed, such as PROSA, ADACOR and, more recently, ARTI holonic architectures (Leitão and Restivo, 2006; Valckenaers, 2019; Van Brussel et al., 1998). Scenario #4 represents a hybrid solution between hierarchical/centralised architecture and a heterarchical one, enabling at the same time local and central interactions among human-machine cells. In this scenario, both human-to-human and machine-to-machine communications are depicted. In fact, in the above-mentioned control architectures, both machines and humans are assumed as *resource* (PROSA and ARTI) or *operational* (ADACOR) holons, namely physical resources present in the shop floor able to perform tasks and communicate with each other. Therefore, machines provided with communication capabilities enable new ways of interactions among the human-machine cells that have been considered as single units so far. In addition to the previously considered interactions (i.e., human-to-machine and human-to-human) a new kind of interaction – machine-to-machine – is represented by orange arrows in Figure 6.4. This interaction can critically affect the human role in the manufacturing process control. In this hybrid scenario, the centralised and decentralised modes are both available as control strategies for the holons/agents; proper switching mechanisms from one mode to another are put in place to have a global optimal behaviour, still maintaining a reactive and responsiveness approach to disturbances (Borangiu et al., 2014; Cardin et al., 2017). Hence, in these systems, humans and machines can be considered independent agents, undertaking actions and making decisions based on the information shared with other agents. In this scenario, the human-in-the-loop approach can include direct or supervisory control over machines (Nunes et al., 2017) because automated negotiations and decisions among machines are allowed even without human intervention. Although in literature this kind of scenario is widely discussed, real implementations in industry are limited and concern mainly the production planning and scheduling activities (Leitao et al., 2016).

Furtherly enhancing this scenario, the paradigm of Industry 4.0 aims at overcoming all the issues emerging from the previously described architectures by enabling a wider communication among all the resources involved. In scenario #5, upgraded human-to-human and machine-to-machine interactions are depicted, supported by Industrial Internet and the Cloud (Gilchrist, 2016). In this case, machines and humans share real-time data and information with all the other agents through a cloud service, which make data and information available from everywhere. Therefore, total information integration is enabled and more efficient process control is guaranteed. Scenario #5 represents a Social Human-in-the-Loop Cyber-Physical Production System, in which vertical integration from shop floor equipment (e.g., machines) to managerial and strategic level can be achieved, and smart machines and equipment form a self-organised system (Wang, Wan, Li, et al., 2016), enabling responsive feedback actions for controlling production processes. Scenario #5 encompasses the advantages of all the previously discussed scenarios. As it occurs in Scenario #3, human operators can benefit of a central information system, but in addition, more information from other human-machine systems can be consulted and examined in real-time thanks to a cloud-based architecture, in order to enhance their situational awareness. To avoid the risk of slowing down the speed of response of the centralised system, decentralised computational capabilities are embedded into machines, which are able to pre-process data. At the same time, similarly to Scenario #4, Social HITLCPPS can take advantage of a hybrid control structure, in which decisions can be taken at decentralised level or through central optimisation strategies that consider the real-time state of all the elements of the system (Gaham et al., 2015).

6.4. A Social Human-in-the-Loop Cyber-Physical System architecture

If the integration of humans is relevant in a single HITLCPPS, in a social environment it is of utmost importance. Above all, two main challenges concern i) the interpretation of human behaviour and ii) the coordination of human agents with other agents. Capturing and understanding the human behaviour requires system identification and modelling techniques difficult to implement, considering the wide physiological, physical and social variables of human being (Munir et al., 2013). In addition, proper orchestration mechanisms are required to coordinate the human work in an environment in which all agents are provided with intelligence and autonomy. Holonic architectures and multi-agent technologies are again suitable solutions to model these mechanisms and support real implementation of Social HITLCPPS. Specifically, in these systems, HMS and MAS can support decision-making based on continuous information exchange at different levels, namely strategic, tactical and operational level (Pacaux-Lemoine et al., 2017).

Wang and Haghighi (2016) propose a CPS architecture combined with HMS holarchy, defining the two layers of physical and cyber processes connected by a network layer (Figure 6.5). Nevertheless, in this architecture, human users are considered as a third party with respect to the system, which interact with physical and cyber elements, pushing decisions, similarly to the concept of "magic human" discussed in Section 6.2.

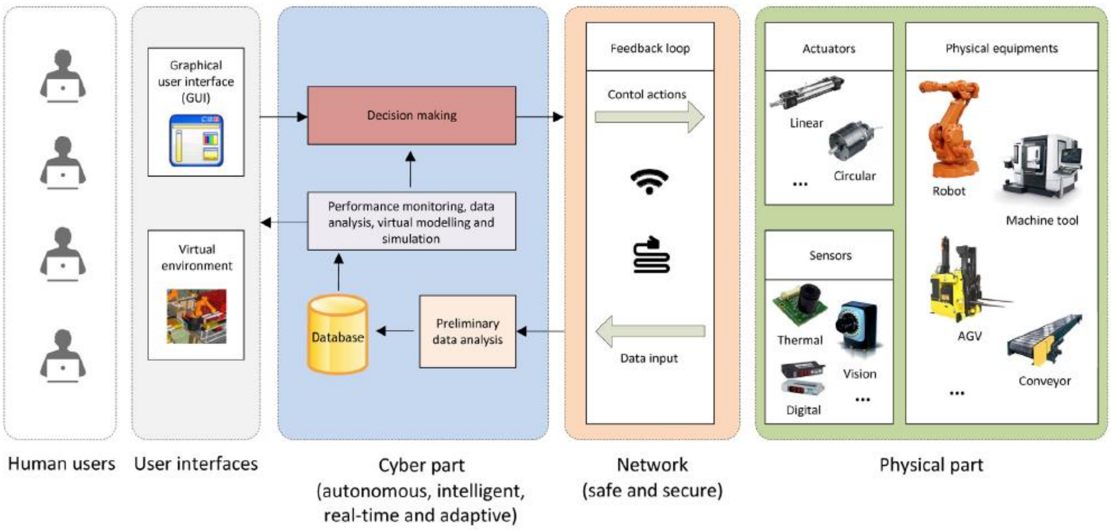

Figure 6.5 – CPS architecture combined with HMS holarchy by (Wang and Haghighi 2016)

Based on this architecture, a Social Human-in-the-Loop Cyber-Physical Production Systems (Social HILCPPS) architecture, based on three layers (physical, control and cyber), is proposed and represented in Figure 6.6. Differently from Wang and Haghighi (2016) where humans are considered external to the manufacturing system and interact with the cyber part through interfaces, in the proposed architecture the cyber and physical layers embed human operators that interact with equipment and information systems.

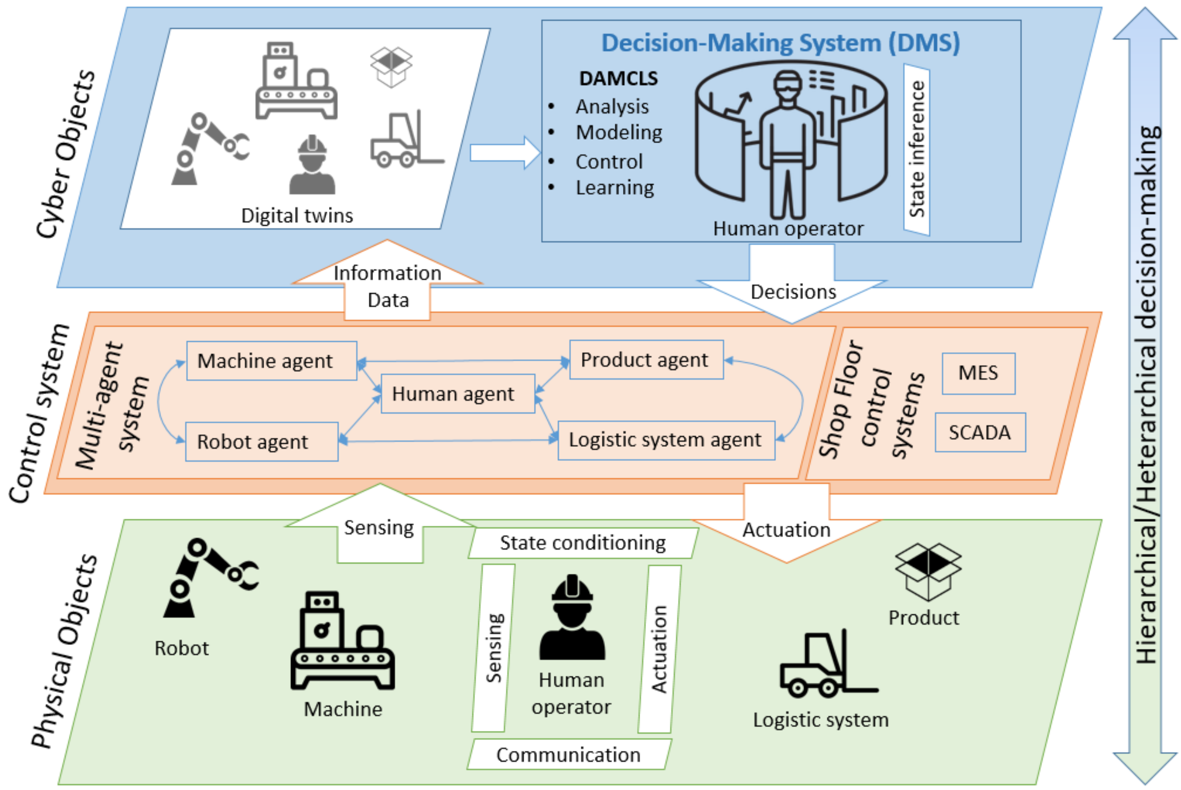

Figure 6.6 – Social Human-in-the-loop Cyber-Physical Production System architecture

In more detail, the three layers are the following:

- **Physical layer**: In the physical layer, humans directly interact with machines, transportation and robot systems, which are embedded with IoT technologies to communicate and with local intelligence to take decisions at a decentralised level. According to the roles of humans in the HITLCPPS reported in operators in the physical layer can contribute to *Data acquisition*, *Communication* and *Actuation*, but also to *State influencing,* depending on their behaviour. In the physical layer, humans and smart equipment can take operational decisions jointly. In some situations, smart equipment can automatically put in place self-adjusting strategies; otherwise, they can communicate with humans to have direct intervention and control. The physical layer is the source of all the data collected from the shop floor that are then sent to the upper levels to be processed and contribute to the decision-making process.
- **Cyber layer**: From the physical layer, data can be sent to the cyber space, to allow for more specific cognitive functions, such as data processing and visualisation as well as virtualisation of the production process. In this layer, human operators can interact with the cyber representation of reality. For instance, they can access raw data collected from sensors and consult central IT systems, such as the ERP. Moreover, they can use applications for data analytics and simulation tools to support the decision-making at strategic level. Indeed, big data and analytics can support companies to improve decisions as well as operational and financial performance (Wang et al. 2016). The interaction of humans at this level fits with the human-in-the-mesh approach presented by Fantini et al. (2016). In fact, the human intervention on the system is not direct to the physical equipment of the factory, but is mediated by software applications, which contribute to the interpretation of the behaviour of the factory elements through a cyber-representation, and allow the operator to take more aware decisions that are then sent to the physical layer. The roles of humans in cyber space mainly concern *State inference.*
- **Control layer:** this middle layer (between cyber and physical layers) encompasses control agents, which mirror and reproduce the behaviour of the single physical objects. This control layer includes both the multi-agent system and shop floor control and execution systems. The holonic and multi-agent control approach is compatible with Shop Floor control systems (e.g., SCADA) and MESs (Simão et al., 2006), which, if properly integrated, can provide real-time information and control over the production system (Qiu et al., 2003). The main features of the control layer can be summarised as follows:
  - Agents collect inputs from physical entities and use them to perform negotiations with other agents.

- Social interactions among physical objects are reproduced by the multi-agent system, thanks to sensors embedded in all the production processes and entities, including operators.
- The control layer provides a model of social interactions among objects to the upper cyber layer.
- Decisions from the cyber layer are transferred to physical objects through actuators.

6.4.1. The decision-making system in the HITLCPPS

The heart of the Social HILCPPS architecture is the Decision-Making System (DMS), which is resident in the cyber layer and takes advantage of the profitable use of data. Only when data are analysed and transformed into knowledge, they can support decision-making processes within organisations (Roden et al., 2017). The DMS is based on the virtual representation of physical objects, which includes all their features, namely their physical and material characteristics, their computational properties, their collected data and their control behaviour. Virtual representations of physical objects are referred to often as *digital twins*, and continuous synchronisation is ensured between the two counterparts (Negri et al., 2017). Control systems, such as the ones represented in the middle layer, can interact with the digital twins influencing the functioning of the whole system (Valckenaers, 2019). The digital twins, reproducing continuously the behaviour of physical objects, contribute to making smart decisions. In Gölzer and Fritzsche (2017), data-driven decision-making processes are discussed with the aim of highlighting the potentials of data usage for automatic feedback-control-loops. In the Social HITLCPPS architecture, we aim at furtherly explore the data proficiency for improving human decisions. In fact, human decision-making is supported by several technologies that enhance cognitive capabilities mainly exploiting data potentialities, which enable real-time monitoring, analytics, optimisation and simulation consequently. Panetto et al. (2019) summarise decision-making tools for supply chain management under the acronym of DAMCLS (namely, Decision Analysis, Modelling, Control and Learning Systems).

Applying the same approach to manufacturing, DAMCLS represented in the proposed architecture encompasses these functionalities:

- *Analysis* - descriptive and diagnostics data analytics that allow performance evaluation and forecasting; such tools can support, for instance, maintenance and logistics.
- *Modelling* - mainly refers to simulation that in turns supports process optimisation, particularly useful when dealing with what-if analysis in the process design phase.

- *Control* - real-time monitoring to enhance visibility and awareness over the production processes; monitoring involves both technical than non-technical parameters of the system (i.e. machine parameters as well as production data).
- *Learning* - includes all the adaptive techniques and algorithms to interpret and acquire knowledge about the functioning mechanisms of the physical system; predictive maintenance and energy management are suitable areas in which learning mechanism can support human decisions.

The Social HILCPPS architecture enables different configurations ranging from a hierarchical to a pure heterarchical based organisation. Beyond the social interaction that occurs horizontally among the objects within the single three layers (i.e. interactions in the physical, control and cyber layers), there is a further vertical interaction between humans in the cyber and physical layers.

On one hand, in a hierarchical structure, the human operator represented in the cyber level is the decision-maker, while the human operator represented in the physical level carries out a mere decision actuator role. On the other hand, thanks to the tools that can augment the cognitive capabilities of the shop floor operator (e.g., wearables, mobile devices), the DAMCLS functionalities can provide an on-field decision-making support for operational and short-term optimisation enabling a decentralised and heterarchical organisation and establishing a better convergence between the human decision-maker supervising the cyber layer with the human operator controlling the physical layer.

6.5.A proposal of roadmap to design the Social HITLCPPS

6.5.1. The impacts of the Social HITLCPPS on HTO

The architecture presented in the previous section aims at representing a conceptual model for identifying the roles of the human in a smart production environment (i.e. a CPPS) and depicting the organisational mechanisms that characterise its functioning. In this sense, it is configured as a theory, namely *"an attempt to explain how a system works, identifying the constituent elements of the system and how they interact and relate each other"* (Karlsson, 2008). For this reason, the model can be also described as a collection of interrelated propositions, which state the relationships between the concepts and variables contained in it. The architecture propositions will require a future validation through on-field research, to ensure the external validity of the proposed approach.

In Table 6.2, the architecture propositions have been summarised and related to the three objects of the HTO model. Indeed, in a socio-technical perspective, implementing a Social HITLCPPS would generate impacts on the three main subsystems, i.e. human, technology and organisation, both bringing benefits and raising issues that require theoretical and practical research development as well as specific attention during the real implementation of this kind of system in practice.

The implications of the architecture implementation that are described in the table can be considered the validation criteria that will be tested in future research.

Architecture propositions	Human	Technology	Organisation
In the physical layer, humans and technology communicate in real-time through interfaces and digital devices.	Technical skills development is required to support the usage of digital devices.	Proper Human-Machine interfaces must be developed.	Pertinent training strategies must be deployed.
All the physical objects are required to communicate with each other.		The IT infrastructure must be developed to support interoperability.	
Data exchange is provided between the three architecture's levels.	Humans need to define the most relevant data flows.	IT security should be ensured.	The data flows and the IT systems to manage them must be organised.
Smart objects in the physical layer can take decisions autonomously.	Humans are in charge of training machines and systems.	Proper technologies for machines' learning and autonomy are required.	
A multi-agent system manages the negotiations among agents.	Humans are involved in the control loops.	Multi-agent systems have to be designed and implemented.	Negotiation mechanisms need to be defined.
Huge quantity of data from several sources is available.	Humans are required to manage data and acquire new analytical skills.	A resilient infrastructure to store and access data is required.	
The decision-making process can be managed both at physical or cyber layer.	Decision-makers can be both operators and managers. Increased autonomy is allowed for some job profiles.	Context-adaptive and autonomous mechanisms are implemented in the machines.	The hierarchical or heterarchical organisation structure must be chosen.
Humans and technology can share the decision-making process.	The decision-making autonomy is defined for each process for each job profile. Flexibility is required to workers.	The decision-making autonomy is defined for each process for each machine.	
Humans can have high visibility on the process through digital representations.	Technical and non-technical skills are required to manage the DAMCLS.	IT tools for DAMCLS have to be developed.	Pertinent training strategies must be deployed. Job profiles' span of control could be redefined.

Table 6.2 – Impacts of the Social HITLCPPS architecture on the HTO elements

From the table, it emerges that the Social HITLCPPS features have manifold effects that in most of the cases involve more than one subsystem. This is due to the fact that the architecture is conceived as a system that integrates human factors and technological aspects and consequently all the features require both developments in the human work and in the technological applications.

As hinted before, the architecture represents a conceptual model, but it could provide a valuable reference model for practitioners who strive for developing a cyber-physical production system by integrating human capabilities with the effectiveness of new technological solutions. Analysing the impacts of the architecture on the HTO is a preliminary step to identify the relevant topics to consider during the design of the real system. In the next paragraph, in fact, a socio-technical roadmap to develop in practice a Social HITLCPPS will be discussed.

6.5.2. The socio-technical roadmap for Social HITLCPPS development

Given the nature of the proposed architecture, it appears clearly that building a real manufacturing system that reproduces the suggested model requires a design and engineering development which involves both technological and human aspects. Actually, the socio-technical approach in systems design has been discussed in literature since many years (Mumford, 2000) and several methods to socio-technical systems design have been described (Baxter and Sommerville, 2011). Generally, these methods aim at encompassing systematically socio-technical thinking in the procurement, specification, design, testing, evaluation, operation and evolution of complex systems. Nevertheless, some issues emerged in applying these approaches, dealing in particular with the multidisciplinary nature of the approach, and the related conflicting objectives of humanistic principles, whose aim is to improve the working life of the humans, and the managerial values, that strive for the fulfilment of the company objectives.

In the literature, some authors already proposed roadmaps for the implementation of Industry 4.0 manufacturing systems (e.g., Ghobakhloo, 2018). However, the existing contributions, often address separately human resources management, smart manufacturing aspects and IT aspects. This is a limitation because, as discussed before, it would not be possible to design an efficient smart manufacturing system without considering the involved workers from the beginning.

For this reason, starting from the already suggested roadmaps towards Industry 4.0 and merging the socio-technical vision, a roadmap for the design and implementation of Social HITLCPPS has been proposed, in order to overcome the literature gap and create some relationships among technological, human and organisational aspects.

In the proposed roadmap, which is depicted in Figure 6.7, the development of Social HITLCPPS includes the choice and implementation of technological applications simultaneously with the design, re-design or upgrade of competences and job profiles.

The 16 steps of the roadmap are described hereafter.

1. *Setting the company objectives*

This first step aims at identifying and defining the objectives that the enterprise wants to achieve with the implementation of the Social HITLCPPS architecture. The definition of company's objectives at strategical level deals with the choice of the most suitable processes to be transformed according to the Industry 4.0 vision, and involves the definition of strategic implementation initiatives, that must be supported with the necessary investments and resources. For instance, the company can identify as a strategic goal to increase the process quality of a specific department and consequently can promote the implementation of a Social HITLCPPS architecture to enhance a better real-time control of the production, in order to monitor and prevent possible deviations from the quality standards. Other strategic objectives can be related to the improvement of the company flexibility and efficiency, or can deal with the deploymnet of new business models, for instance the re-definition of the company's product-service offering. Setting the objectives includes, along with the definition of the involved processes that will be modelled according to the architecture, the identification of the related functional or business areas (such as logistics area, maintenance area, etc.) and of the most relevant stakeholders.

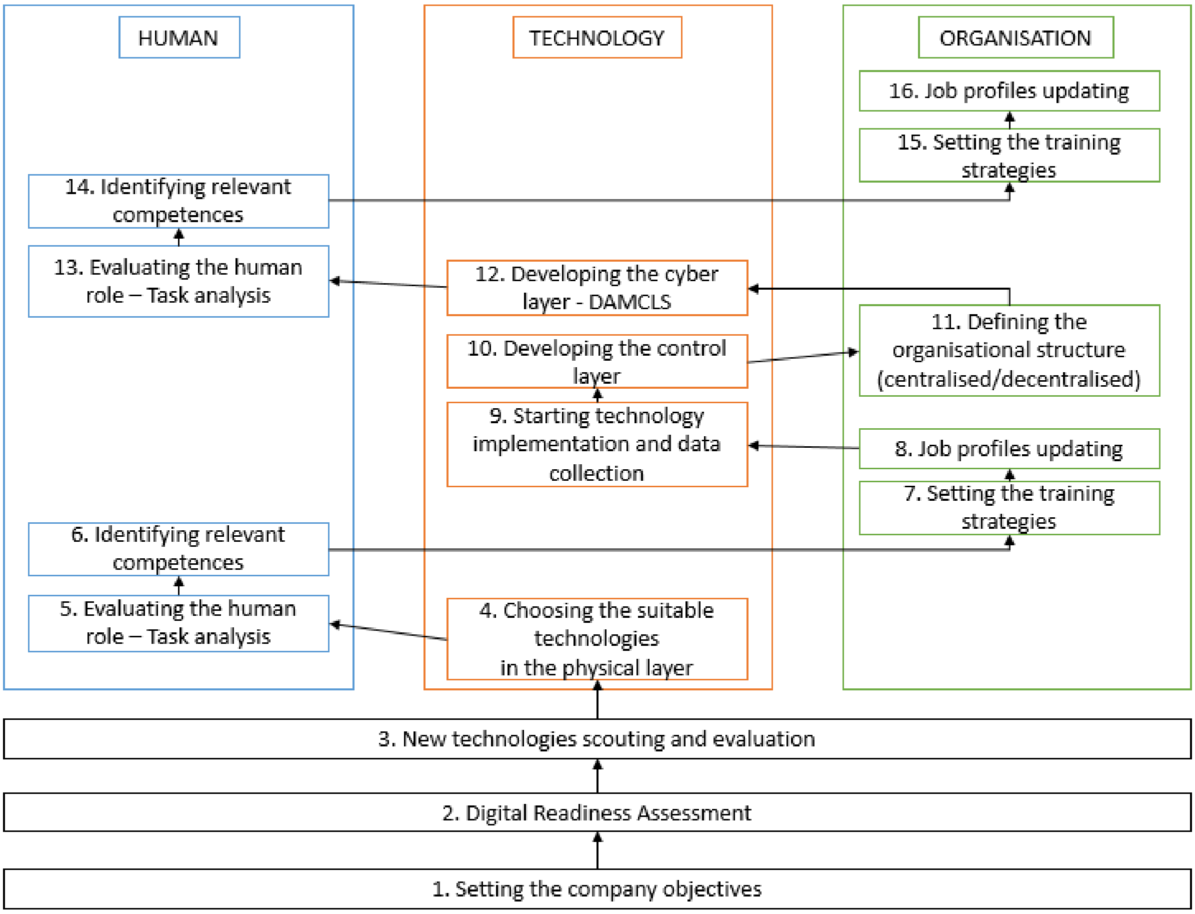

Figure 6.7 – Roadmap for the development of a Social HITLCPPS

2. *Digital readiness assessment*

After the goals definition, companies are required to assess their current level of development with regard to the Industry 4.0 vision. Maturity and readiness assessment tools provide systematic frameworks enabling benchmark and performance improvement. Generally, they include a series of descriptions of business performance for specific companies' aspects and domains, such as technology, people, operations, organisation and so on. The descriptions are ordered into levels of capability from "not able to do it" through "continuously improving". Using these tools, organizations are allowed to develop their own strategic roadmap defining the development directions to understand and facilitate their transition toward Industry 4.0 (see e.g., Colli et al., 2019; Pirola et al., 2019).

3. *New technologies scouting and evaluation*

After the assessment of its current capabilities, the company can start a technological scouting to take knowledge about the available opportunities offered by the market. In this step, several possibilities of technology implementation should be evaluated in relation to the set objectives.

4. *Choosing the suitable technologies in the physical layer*

According to the defined objectives and as a result of the technology evaluation, the company should start developing the physical layer from a technological perspective. This includes, for instance, the choice of technologies for the specific company manufacturing processes, such as machines, robots, etc. In particular, as proposed in the architecture, the physical devices must be able to communicate and share data among them and to an upper level. This requires the design of proper communication infrastructure and the implementation of sensors able to collect data from the more critical processes.

5. *Evaluating the human role – Task analysis*

The choice of implementing specific technologies in the physical layer has immediate impacts on the role of workers. For this reason, a first evaluation of how the tasks of the involved humans would change is required. To do this, the TCF methodology, which has been proposed in Section 4, can be used and applied to specific job profiles that are expected to interact with the new technologies. In this step, the identification of the tasks sets before and after the technology introduction will allow the re-balancing of the operators' workloads and it is preparatory to the following steps.

6. *Identifying relevant competences*

In step 3, the set of activities that workers need to perform in the updated manufacturing process are identified. This allows evaluating, in this step, the competences that are required to manage those tasks. As suggested in chapter 5, it could be useful to analyse the required competences according to a classification in technical/non-technical ones. In doing this, competences gaps can emerge.

7. *Setting the training strategies*

To cover the previously identified competence gaps, in this step, it could be necessary to develop proper training strategies. This can include specific technical training on the implemented technologies and devices, but also methodological training to cope with the new collaborative environment. The training strategies are crucial to prepare workers to deal with the new technologies and involve them in a successful transformation of the manufacturing processes.

8. *Job profiles updating*

In the light of the previous needs in terms of tasks and competences, existing job profiles can be updated or new job positions can be created. In particular, job profiles in the IT area could be required, as well as specific roles in charge of coordination and innovation management.

9. *Starting technology implementation and data collection*

Once the technical infrastructure has been chosen and the role of human has been defined, it is possible to start with the technology implementation, which concerns the physical installation of new machines, devices or equipment, along with the implementation of proper applications for data collection.

10. Developing the control layer

At this point, the design of the control layer is required. It concerns the choice of traditional shop floor control systems, such as MES applications, but can also include a more complex development of multi-agent control architectures. In many cases, in the transition towards a Social HITLCPPS, this step concerns the adaptation or retrofitting of an existing control layer, according to the new needs of integrating the human control or the decentralisation of some decisions. In particular, developing a multi-agent control system requires that every physical object (including humans) is modelled as an agent and its behaviour must be defined, along with the control mechanisms that regulate the interactions with other agents.

11. Defining the organisational structure (centralised/decentralised)

In relation to the control layer, the organisational structure of the process can be re-defined. In particular, these steps concern the adaptation of the organisation structure to the previously defined control strategy, which can be centralised, decentralised or hybrid. Revising the organisational structure of the enterprise can lead to changes in the span of control for some job profiles and have an impact on the number of hierarchical levels.

12. Developing the cyber layer – DAMCLS

Once the data from the physical layer are available and the shop floor control strategy has been set, the cyber layer should be developed in order to support the human decision-making, the so-called Decision Analysis-Modelling-Control-Learning systems. Also in this case, proper interfaces should be developed to allow the operators to access and analyse the data that come from the shop floor. In this step, the cyber representations of the physical objects (i.e., the digital twins) are created and made available for the human decision-makers.

13. Evaluating the human role – Task analysis

Similarly to step 3, a new assessment of the human role in the manufacturing process should be performed. The cyber layer, in fact, offers new opportunities to enlarge the tasks set of some job profiles, in particular those ones related to management. Also in this case, the implementation of DAMCLS can modify the activities performed by workers and a task analysis with the TCF methodology could be useful to identify these changes.

14. Identifying relevant competences

As it occurs in step 4, depicting the tasks set of job profiles after the technology introduction can be useful to identify the relevant competences and highlight possible competence gaps.

15. Setting the training strategies

Similarly to step 5, any competence gap can be fulfilled only promoting proper training strategies, which are again related both to technological application (i.e. the DAMCLS) and to managerial aspects.

16. Job profiles updating

Finally, a new update in job profiles could be required. In particular, new job profiles can be created, in relation to the need for qualified workforce able to extract the most of value from the data available from the shop floor. Also current managerial roles that are in charge of decision-making can be required to cope with data analysis activities, thus enlarging their tasks set.

As it is possible to notice, the proposed roadmap reflects the functioning of the Social HITLCPPS architecture. First, the physical layer should be developed, taking in consideration previously the technological aspects and immediately after the human-related aspects. After that, the control layer must be developed and this can produce impacts in the organisational sphere, modifying the hierarchical structure of the enterprise/process. Finally, the cyber layer is developed and, similarly to physical layer, the design should take in consideration technology and human-related aspects together. For these reasons, step 13 to step 16 are similar to step 5 to step 8.

6.6.RQ3 outcome

The aim of this chapter was to answer research question 3:

> **How does a human-centred perspective affect the integration of Industry 4.0 technologies and humans into next generation production systems?**

To answer RQ3, the coexistence of technology and humans in manufacturing systems has been addressed as a socio-technical system, thereby discussing a taxonomy of human roles in smart factories. According to the presented research, it is possible to state that technologies supporting physical capabilities of humans are particularly useful to enhance the sensing and actuation role of human operators, whereas communication skills and inference capacity are upgraded by many cognitive technologies, which augment human capabilities in processing and sharing information.

Keeping the human operator at the centre of the analysis, in order to depict the integration of Industry 4.0 technologies and humans into next generation production system, five scenarios in the evolution of control organisations towards the smart factory paradigm have been identified. This led to the proposal of a Social Human-in-the-loop Cyber-Physical Production System architecture, which determines that the integration of human operators and technology in a CPPS can be attained through a three-level perspective where a *physical layer* and a *cyber layer* embed human operators that interact with equipment and information systems in a *control layer*. In turn, the control layer makes use of an agent-based perspective to address social interactions and decision-making processes through different types of configurations (from hierarchical to pure heterarchical) of the organization.

As a step further, the impacts of implementing such architecture have been related to the HTO socio-technical model, which have been chosen as a reference for this research work. Finally, a roadmap for the development of Social HITLCPPS architecture-based manufacturing process has been depicted in 16 steps.

This study extends the available literature, enabling an extensive and comprehensive understanding of the role of humans in the development of the next generation manufacturing systems, and depicting the data-driven decision-making processes of a smart factory. The in-depth analysis of human-technology interactions in a CPPS can guide practitioners in defining the most suitable technologies to support the human work, according to their own company strategy.

This research outlines the importance of properly integrating humans in cyber-physical production systems. Moreover, companies that are changing their operational processes towards the Industry 4.0 paradigm, can benefit from the formalisation of the three-layer architecture, in which the relationships between humans, technologies, and data flows are represented.

6.6.1. Relationship between RQ3 outcome and the other RQs

The RQ3 aimed at reflecting on the impacts of smart manufacturing on the human work from a more general perspective, embracing as a whole all the topics of Human, Technology and Organisation (see Figure 3.1). The Social Human-in-the-Loop Cyber-Physical Production Systems architecture, in fact, tries to consider and merge all these elements in a unique framework.

In order to support practitioners in the implementation of such an architecture, a roadmap is proposed as well. In its conception, the roadmap takes advantage from the RQ1 and RQ2 outcomes and proposed tools, which are implemented at different steps to carry forward in a synergistic way the technological development and redefinition of the role of humans and the related human-technology interactions.

7. Conclusions

In recent years, the introduction of digital technologies in the manufacturing industries paved the way to the evolution of traditional industrial systems towards the smart manufacturing concept. The radical changes that have been expected from the development of innovative technologies finally promoted the idea of a Fourth Industrial Revolution, the so-called Industry 4.0. The Industry 4.0 initiative has been conceived in order to face the market and social trends that are still driving industrial companies, which nowadays are required to become increasingly flexible and agile to respond to the customer requirements in an effective way, also fulfilling the needs of individualization in the demand. To achieve flexibility, faster decision-making procedures are necessary; further, the production systems must be not only adaptive but also self-adjusting and self-optimized. In addition, environmental issues encourage the manufacturing enterprises to implement sustainable production processes, in order to maximize resource efficiency and minimize the waste of energy and materials. The Industry 4.0 paradigm has opened high potentialities to implement new business and operational models. Many manufacturing companies around the world have been encouraged to invest in research and industrial projects to enable the realization of smart factories.

Despite the strong commitment to the development of fully connected manufacturing systems, there are several implementation barriers, not exclusively technology-related. In particular, the introduction of smart and digital technologies in manufacturing is expected to generate relevant impacts on the workforce, changing the nature of human work and affecting organisational variables. From the review of existing literature about the topic, it emerged that the impacts of Industry 4.0 on the human work and the new role of operators in the smart factories context are under-researched and required further investigation.

For this reason, the aim of this work was to address the Industry 4.0 paradigm from a socio-technical perspective, investigating the impacts of the technology introduction on several aspects of the human work. In particular, the HTO model has been used as the reference model to describe and analyse the impacts of Industry 4.0 paradigm on the human work and three research questions have been pointed out:

- **RQ1. How do smart technologies affect the tasks of the operator in the context of Industry 4.0?**
- **RQ2. What are the competences required by introducing new work attributes that exploit Industry 4.0 technologies?**
- **RQ3. How does a human-centred perspective affect the integration of Industry 4.0 technologies and humans into next generation production systems?**

The first research question concerned the changes that affected the work activities (i.e., the tasks) performed by operators in relation to the introduction of new technology able to assist and augment human capabilities as well as able to fully replace the human presence. To provide the answer to the research question, a Task Classification Framework (TCF) has been created, aiming at representing the tasks' set of the operators according to three relevant characteristics. In particular, tasks can be classified as Routine/Non Routine, Physical/Cognitive, Social/Individual. Based on this framework, a methodology in four steps has been developed in order to assess how the tasks of the operators can be subjected to modification after the introduction of new technologies. The first step concerns the *Identification of traditional tasks*, which are mapped into the TCF. The second step is the *Smart Technologies classification*, which consists in understanding what are the tasks' areas in which technology can support or replace human tasks. The third step is the *Identification of changing tasks*, that is a new mapping of the tasks' set after the technology introduction. Finally, due to the possible changes in the work amount of the operator, a fourth step is related to the *Re-balancing of the task allocation after the introduction of technology*. The Task Classification Framework and the related methodology represent a useful tool that companies can adopt in a preliminary step of digital transformation to the identify the new requirements in terms of skills and competences which are related to the technology adoption. In fact, they enable to identify what are the activities that can be easily replaced by technology and what are the new tasks that are created, which are expected to concern increasingly cognitive areas, requiring an upskilling of workers not only in technical domain but also in social relationships management. The TCF methodology has been applied to the industrial case of Brembo, in particular to the job profile of the assembly lines manager.

As a consequence of the first RQ that raised the need to develop proper upskilling programs to face the changing tasks' set in smart manufacturing systems, the second research question concerned the identification of the relevant competences for Industry 4.0, with a parallel investigation about job profiles and organisational structure which are directly affected by the I4.0 transformation. The development of the answer to this research question has been addressed through two different multiple case studies, which have been conducted in manufacturing companies located in the North of Italy. In both the case studies, conceptual frameworks have been provided as a foundation to conduct the investigation through in-depth interviews and direct observation of the companies. In particular, in the first case study, the relationships between the technology and competences, job profiles and organisational structure has been explained, highlighting these main aspects: i) with increasing adoption of I4.0 technologies, companies will first experience the need to develop technical competences, while the need to develop methodological, personal and interpersonal competences will arise in more advanced stages; ii) introducing I4.0 technologies is linked to the development of a new job profile, characterised by a relatively high degree of autonomy and intermediate horizontal specialisation, combining technical and non-technical competences (i.e., 'Autonomous Operative Job Profile'); iii)an organisational structure characterised by a wide span of control and a low number of hierarchical levels is associated with the adoption of I4.0 technologies. The second case study provided a more specific investigation of competence development for Industry 4.0 in relation to the servitization process that is commonly called digital servitization. In a similar way to what was found in the first case study, the second case also showed that, in order to support the technological transformation of companies, technical and methodological skills are perceived as the most urgent and relevant. However, in order to achieve results of broad integration and more complex ecosystems-based business models, personal and social skills will be crucial in the future.

Finally, the third research question aimed at encompassing all the previously discussed aspects about the impacts of technology on the human work, finally providing a more general view of the role of humans in the next generation manufacturing systems, namely in the smart factories. To this purpose, the human-technology integration has been discussed and the concept of Human-in-the-Loop Cyber-Physical Production system has been presented. In these systems, humans can be involved in different roles (i.e., data acquisition, state inference, state influencing, actuation) and several communication and organisation methods can be used to control the human-machine integration in the factory (i.e., centralised/decentralised/hybrid approaches).

In the context of Industry 4.0, the attempt to integrate the human capabilities and roles with the technology led to the proposal of a three-layer architecture, the Social Human-in-the-Loop Cyber-Physical Production System Architecture, in which humans are integrated into the smart factory both at physical and cyber level. Moreover, the heart of the Social HILCPPS architecture is the Decision-Making System (DMS), which is resident in the cyber layer and takes advantage of the profitable use of data, while the architecture enables different configurations ranging from a hierarchical to a pure heterarchical based organisation.

In order to provide further managerial implications of this research, the impacts of this architecture on the human-technology-organisation subsystems have been analysed. Finally, a roadmap to support engineers in the socio-technical design of Social HITCPPS has been proposed, with a specific focus on integrating technological and human aspects in the development phases.

7.1.Strengths of the PhD research

This thesis is the result of a long-time investigation on the topic of Industry 4.0 and it aims at contributing to highlighting the human aspects in the research stream of smart manufacturing system.

Indeed, this PhD research was born in the context of an industry-academia collaboration and it is strongly founded on a relevant industrial experience. The PhD candidate spent about three years (two of the three during the PhD programme) in the company Brembo SpA, a worldwide leader in the automotive sector, which has been traditionally considered one of the most technologically advanced sectors in industry able to lead all the other industrial sectors. Given the strong push to innovation of the company, the author has been allowed to observe from a privileged point of view how companies are facing the digital transformation, being able to identify the great opportunities but at the same time the critical issues, including certainly the need to change in some ways the culture and operating methods of workers. The industrial experience has been the basis for the definition of the PhD research topics and offered, at the same time, the possibility to test the RQ1 proposed methods in a real context.

The link to the industry, that is the first strength of this research, is related also to the on-field research that has been conducted for RQ2, that has been part of a project in collaboration with Confindustria (the Italian industrial association), in order to provide managerial implications.

In addition, to address the research topic as broadly as possible, during the PhD development various methodological approaches were used. For this reason, along with the on-field investigation through case studies and action research, a more conceptual approach has been used to contribute to theory building.

Finally, the PhD research was favoured by the collaboration with other relevant research groups. Given the socio-technical approach that has been used, the discussion with researchers from other disciplines, in particular from labour market studies and economic and management engineering, has been carried out continuously. Also the collaboration with foreign researchers on the topics of Operator 4.0 and Digital Transformation was fundamental to develop and support the validity of the RQ outcomes.

7.2. Limitations and further developments

This thesis suggests different reflections that both researchers and managers should pursue in the near future. Nevertheless, despite the author's attempt to contribute in a wide manner to the research about the impacts of the introduction of Industry 4.0 technologies on the industrial workforce, the research discussed in this thesis presents some limitations that will be overtaken by further developments and improvements.

According to the research presented in Section 4 in response to RQ1, only one application has been developed. It would be useful to validate the TCF applicability and usefulness also in other manufacturing companies. Having the possibility to address the TCF methodology in several contexts and for different workers would be relevant to look for similarities in the changing tasks' set of workers. Based on the task analysis, for instance, it would be possible to provide forecasting about how the different kinds of job profiles will evolve, such as the shop-floor operators, the maintenance operators, the middle-management job profiles and so on. This will contribute much longer to the debate about how human labour will change in the future.

With regards to the case studies developed to answer to RQ2, the research has been based on a small sample of companies, while more enlarged research will allow a more comprehensive discussion about competence development in the Industry 4.0, both for manufacturing companies and in relation to the digital servitization phenomenon. A methodology based on survey research could also be useful to reach a sizeable number of enterprises. Further developments in this topic could include the formalization of the possible roadmaps to be followed by companies and the definition of specific competences required in relation to some relevant companies' features (such as the business, the customers, etc.) and according to different job profiles and levels (such as for managers, operators, etc.). In this way, managers will be supported in the choice of proper competences development programs as well, while academia can align the education offering according to these suggestions.

Finally, an empirical validation of the Social HITLCPPS Architecture would be performed, in order to test the applicability of such a scenario to a real context. Since, due to the complexity of the proposed model, it has not been possible yet to provide its external validity through an on-field evaluation, the criteria for the future validation have been envisioned, in the form of implications that the architecture would have on a real production system. The empirical application of the architecture will allow the development of refined mechanisms to regulate the hierarchical/heterarchical structure of decision-making, which are difficult to define at a general level. Indeed, a sharp distinction between operational, tactical and strategic decision levels cannot be defined universally and deep knowledge about the specific smart factory requirements is requested to allocate decisions to each level ensuring both the flexibility and robustness of the manufacturing process. Moreover, starting from the suggested architecture, instructions and rules to design a smart factory environment could be provided in further research. They concern technologies that support human work, cooperation aspects between humans and machine, social interactions in complex systems, as well as other specifications about the architectural structure of decision-making. These instructions could be also differentiated in relation to the production system typologies. In particular, different levels of intelligence and automation are related to decision capabilities in the equipment and define different control task allocation between humans and machines. For this purpose, it is worth mentioning that to achieve the best performance in a smart factory development, manufacturing process and human work design must be carried out simultaneously.

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APPENDIX A

Competence model by Hecklau et al. 2016

Category	Required competencies	Context	Comparative references
Technical competencies	State-of-the-art knowledge	Due to increasing job responsibility knowledge is getting increasingly important	[26, 27]
	Technical skills	Comprehensive technical skills are needed to switch from operational to more strategic tasks	[26, 28]
	Process understanding	Higher process complexity demands a broader and deeper process understanding	[27, 29, 30]
	Media skills	Increasing virtual work requires employees to be able to use smart media, e.g. smart glasses	[26, 28, 31]
	Coding skills	Growth of digitized processes creates a higher need for employees with coding skills	[26, 31, 32]
	Understanding IT security	Virtual work on servers or platforms obligates employees to be aware of cyber security	[27, 30, 31]
Methodological competencies	Creativity	Need for more innovative products, as well as for internal improvements, requires creativity	[26, 31, 32]
	Entrepreneurial thinking	Every employee with more responsible and strategic tasks has to act as an entrepreneur	[26, 31, 33]
	Problem solving	Employees must be able to identify sources of errors and be able to improve processes	[26, 28, 31]
	Conflict solving	A higher service-orientation increases customer relationships; conflicts need to be solved	[26]
	Decision making	Since employees will own higher process responsibility, they have to make their own decisions	[26, 28, 31]
	Analytical skills	Structuring and examining large amounts of data and complex processes becomes mandatory	[26, 31, 33]
	Research skills	Need to be able to use reliable sources for continuous learning in changing environments	[31]
	Efficiency orientation	Complex problems need to be solved more efficiently, e.g. analyzing growing amounts of data	[29, 33]
Social competencies	Intercultural skills	Understanding different cultures, especially divergent work habits, when working globally	[28, 32]
	Language skills	Being able to understand and communicate with global partners and customers	[32]
	Communication skills	Service-orientation demands good listening and presentation skills, whereas increasing virtual work requires sufficient virtual communication skills	[26, 32, 33]
	Networking skills	Working in a highly globalized and intertwined value chain requires the knowledge networks	[26, 31]
	Ability to work in a team	Growing team work and shared work on platforms expects the ability to follow team rules	[26, 30, 31]
	Ability to be compromising and cooperative	Entities along a value chain develop to equal partners; every project needs to create win-win situations, especially in businesses with increasing project work	[26, 31]
	Ability to transfer knowledge	Companies need to retain knowledge within the company; especially with the current demographic change, explicit and tacit knowledge needs to be exchanged	[26, 30, 31]
	Leadership skills	More responsible tasks and flattened hierarchies make every employee becoming a leader	[27]
Personal competencies	Flexibility	Increasing virtual work makes employees become time and place independent; work-task rotation further requires employees to be flexible with their job responsibilities	[26, 31–33]
	Ambiguity tolerance	Accepting change, especially work related change due to work-task rotation or reorientations	[26, 30, 33]
	Motivation to learn	More frequent work related change makes it mandatory for employees to be willing to learn	[30, 33]
	Ability to work under pressure	Employees involved in innovation processes need to cope with increased pressure, due to shorter product life cycles and reduced time-to-markets	[31]
	Sustainable mindset	As representatives of their companies, employees also need to support sustainability initiatives	[26]
	Compliance	Stricter rules for IT security, working with machine, or working hours	[31, 32]

APPENDIX B

Case study A: Interview protocol

OBJECTIVE OF THE INTERVIEW: Investments in so-called I4.0 technologies, identify and bring out:

- The birth, evolution and disappearance of roles and tasks
- The impact of the adopted technologies on the skills required of workers
- Organisational changes introduced by technology adoption
- Expectations and issues related to investments

<u>A. ENTERPRISE</u>

- DESCRIPTIVE DATA
- STRATEGIC OBJECTIVES
- PRODUCT FAMILIES
- COMPANY ORGANISATION CHART
- ANNUAL SHARE OF INVESTMENTS IN R&D (% OF TURNOVER)
- INVESTMENT NEWS I4.0 FROM SITE / ARTICLES

<u>B. TECHNOLOGY INVESTMENTS I4.0</u>

- HOW IS THE COMPANY INVESTING? (AREAS AND TECHNOLOGIES)
  - Concerning the so-called I4.0 technologies, in which area is the company mainly investing?
    - Manufacturing, logistics, after-sales, maintenance, product development, other?
    - Which business processes have been involved (transversality)?
  - In which particular technologies?
    - Advanced Manufacturing solutions (reconfigurable technologies)
    - Advanced robotics (e.g., exoskeletons)
    - Collaborative robotics (e.g., robots)
    - Augmented reality
    - Product simulation (e.g., digital twin)
    - Process simulation
    - Big Data Internet of Things (Iot) (big data and analytics, e.g., predictive maintenance through data analytics)
    - Cybersecurity

        - Other technologies included in the ‘Calenda Plan’ (additive manufacturing, horizontal/vertical integration, industrial IoT, cloud)
    - For each technology indicated, at what level of adoption is the company currently (1 to 6)?
        - Non-use
        - Orientation
        - Preparation
        - Test
        - Systematic use
        - Optimisation and integration

- BENEFITS/OBJECTIVES RELATED TO INVESTMENTS
    - Why were the investments made? What were the desired benefits? (ex: increased efficiency and self-sufficiency)
    - At what point is the project related to the investment? In the investment plan for the project, what investments have already been made, and what investments are planned for the future?
    - What were the benefits of the investments made? Do they coincide with those desired?
    - Have you encountered any problems with the implementation?
    - What types of risks did you consider about the investment, and how did you manage them?
    - Have you received funding/incentives?
    - Have investments in new technologies led to changes in the volume of the workforce or movements? Has there been any change in the geographical location of production facilities?

- HOW WAS THE INTRODUCTION OF INNOVATION PROGRAMMED AND MANAGED (how was it communicated, steps, timing, modalities, the involvement of workers)?
    - Has the company participated in external training courses on I4.0?
    - What is the level of individual knowledge concerning I4.0? (for the person interviewed and for the decision-makers who chose to introduce the innovation)
    - Does the company have active Alternating Work School programs?
    - Has the company had the support of external consultants? (e.g., evaluating investments and possible financing, defining the implementation phases of innovation in the I4.0 field)
    - Is there resistance to change on the part of the company’s employees?

- TECHNICAL SKILLS
    - Were any innovations entirely new for the company?
    - Have you noticed a lack of technical expertise as a result of introducing new technologies?
    - What investments have been made in terms of training and education?

- After implementing the innovation, did you need assistance from the supplier to develop the skills required to use it?
- Are the company's infrastructures sufficient to support the innovation introduced? (ex: all data in the cloud, but slow connection; each time you access the files the time required is long).
- Have working groups been set up to manage technological innovations?

C. IMPACTS ON ORGANISATION (MACRO LEVEL)

- MACROSTRUCTURE/STAFF/DECISION POWER (always ask for the reasons for the changes)
  - About the above investments and innovations, has the company's organisational chart changed? How?
  - Have organisational units been outsourced or internalised?
  - Has there been an impact on the orientation of your business as a result of these changes? (more customer-oriented, service-oriented, sustainable, etc.)
  - Has there been a reduction (or increase) in hierarchical levels? How was it possible to achieve this? (more significant delegation to lower levels, transversal figures, centralisation/decentralisation of decision-making power, etc.)

D. IMPACTS ON THE ORGANISATION (MICRO LEVEL)

- TYPE AND QUALIFICATION OF THE ROLE IMPACTED
  - Which jobs/roles/missions have been affected by the innovative change?
  - Has the individual's work changed at an operational level? (e.g., the impacted role has the same actions as before or was adapted to new work processes).
  - For impacted roles, was it necessary to increase or decrease the scope of control (number of people coordinated)?
  - Have they received more or less responsibility?
  - Have there been any changes in the hierarchical position?
- DESCRIPTION AND QUALIFICATION OF TASKS (VARIETY/VOLUME/SPEED)
  - About the tasks of the impacted roles, how have they changed in terms of variety (number of different tasks to be performed)?
  - Do the tasks include more interdisciplinary activities (e.g., not only technical activities but also organisational/analysis activities), or are they very specialised?
  - Has the change in tasks led to a change in production volume (quantity of output/number of interventions carried out)?
  - How have they changed in terms of speed (time required to carry out the different tasks assigned)?

- CONTENT OF THE WORK - COGNITIVE CONTENT / POLYVALENCE AND AUTONOMY / PHYSICAL ENVIRONMENT
    - Do the new tasks require more sophisticated technical skills?
    - Do the new tasks require more complex collaboration/interaction skills?
    - Did the impacted roles have to develop new knowledge?
    - How did the new knowledge develop? How were the workers trained?
    - As a result of innovation, do the impacted roles operate alone or in teams?
    - Should the workers make their own decisions? Alternatively, should they follow standardised procedures? (e.g., greater autonomy in decisions, controlling the operations of a machine or even reworking the results)
    - Are the new tasks expendable in different contexts compared to those for which they were designed (polyvalence/flexibility)?
    - Have changes been made to the working environment? (e.g., workplace layout changes; time optimisation)

E. COLLABORATION AND COORDINATION (IMPACT AT BOTH MICRO AND MACRO LEVELS)

- How have the different organisational units coordinated changed?
- Have courses been made to increase aptitude for teamwork?
- Have virtual collaboration methods (chat, information systems, teleworking, etc.) been introduced?
- Have there been any changes in the time devoted to developing social relations and strengthening the working network (e.g., corporate events, meetings, courses)?

F. IMPACT ON SKILLS OF ORGANISATIONAL CHANGES (MACRO, MICRO AND COLLABORATION)

- Were actual figures trained and instructed to develop new skills? Which ones?
- Have new figures been hired? If so, which ones? Of what extraction? (technical, economic, managerial, IT, etc.)
- Were the workers able to adapt to the change? Are they able to manage the work? Do workers work together, proactively?

APPENDIX C

Case study B: Interview protocol

A. ENTERPRISE

- DESCRIPTIVE DATA
- STRATEGIC OBJECTIVES
- PRODUCT FAMILIES
- COMPANY ORGANISATION CHART
- ANNUAL SHARE OF INVESTMENTS IN R&D (% OF TURNOVER)
- INVESTMENT NEWS I4.0 FROM SITE / ARTICLES

B. MACROTREND

- HOW IMPORTANT AND IN WHICH WAY ARE THESE TRENDS IMPACTING / WILL IMPACT IN YOUR REALITY?
  - Servitization
  - Digitalisation/Industry 4.0
  - Circular economy
  - Smart working

C. TECHNOLOGY INVESTMENTS I4.0

- REFERRING TO THE FOLLOWING TECHNOLOGIES, HOW IMPORTANT ARE FOR YOU? IN WHICH WAY AND SCOPE PROCESSES ARE IMPACTING / WILL IMPACT?
  - Advanced Manufacturing solutions (reconfigurable technologies)
  - Advanced robotics (e.g., exoskeletons)
  - Collaborative robotics (e.g., robots)
  - Augmented reality
  - Product simulation (e.g., digital twin)
  - Process simulation
  - Big Data Internet of Things (Iot) (big data and analytics, e.g., predictive maintenance through data analytics)
  - Cybersecurity
- HOW RELEVANT ARE THEY AND IN WHICH WAY ARE IMPACTING / WILL IMPACT ON YOUR SERVICE OFFERING?

D. NEW COMPETENCES AND ROLES

- WHICH ARE THE COMPETENCES RELATED TO INDUSTRY 4.0 THAT THE COMPANY SHOULD ACQUIRE / DEVELOP TO GOVERN THE ONGOING TRANSFORMATIONS?
- WHICH ARE THE NECESSARY ROLES IN ORDER TO HANDLE AND EXPLOIT THESE TRANSFORMATIONS?
- WILL IT BE NECESSARY TO ADD NEW RESOURCES OR WILL IT BE POSSIBLE TO RETRAIN THE ALREADY EXISTING ONES? THE COMPANY NEEDS IN TERMS OF COMPETENCES MUST BE SATISFIED WITH THE INTRODUCTION OF THE NEW RESOURCES?

E. OBSTACLES

- WHAT ARE THE PRINCIPAL OBSTACLES OF DEVELOPING/INTEGRATING THE NEW COMPETENCES IN THE COMPANY?
- ARE THERE ANY DEVELOPMENT ACTIONS OF THE ON PROGRESS COMPETENCES IN THE COMPANY?

APPENDIX D

Case study B: Description of the companies

Company	Industry	Present service offering	Future service offering
A	Large forklift and earth moving machines provider	Rental of machines equipped with embedded sensors that allow remote monitoring and fleet management. The company provides additional consultancy services, supporting customer's operations.	Platform's implementation for data collection and analysis from the installed base. Development of self-diagnosis technologies to enable predictive maintenance.
B	Large solutions for textile manufacturer	Sales of machines equipped with embedded sensors. The company provides remote data management tool. Moreover, machine learning and artificial intelligence technologies are used to provide predictive maintenance.	Development of a cloud platform solution for data management. Enlargement of service portfolio with new advanced services, such as maintenance based on virtual and augmented reality and spare parts provision based on additive manufacturing technology.
C	Medium assembly machines manufacturer	Sales of machines equipped with embedded sensors. The company also provides data acquisition tool allowing data sharing towards enterprise information systems.	Use of monitoring technologies to enable advanced services, such as predictive maintenance. Real-time communication between machines, products and humans. Implementation of self-diagnostics and self-configuring algorithms.
D	Large machine tools manufacturer	Sales of machines equipped with embedded sensors. Although remote data monitoring tool is available, the offering is still product-based and only base services are provided.	Development of data analysis tools and platform for advances services based on data management and sharing. Use of monitoring technologies to enable advanced services, such as condition-monitoring maintenance.
E	Medium energy machines manufacturer	Sales of machines equipped with embedded sensors. Although remote data monitoring tool is available, the offering is still product-based and only base services are provided.	Development of a cloud platform solution in order to provide advanced services based on data management and analysis.
F	Large sensors and identification solutions provider	Sales of technological solutions to collect, monitor and analyze data by enabling condition-monitoring and anomaly detection tools.	Development of platforms and dashboards for big data management and analysis. Integrated solutions development for collection and networking of data from different sources.
G	Large machines for chemical industry manufacturer	Sales of machines equipped with embedded sensors. Although remote data monitoring tool is available, the offering is still product-based and only base services are provided. Cloud storage of data is available as well.	Improvement of current advanced services, including new data analysis tools for maintenance management, and cloud-based services
H	Large CNC machines manufacturer	Sales of machines equipped with embedded sensors. Although remote data monitoring tool is available, the offering is still product-based and only base services are provided.	Enlargement of service portfolio with advanced services, based on data analysis, and cloud-based services.

APPENDIX E

Case study B: Classification of competences

Company	Technical	Methodological	Social	Personal
A	▪ Coding skills ▪ Media skills ▪ Process understanding ▪ State-of-the-art knowledge ▪ Technical skills ▪ Understanding IT security	▪ Analytical skills ▪ Creativity ▪ Efficiency orientation ▪ Entrepreneurial thinking ▪ Problem-solving	▪ Ability to be compromising and co-operative ▪ Communication skills ▪ Leadership skills ▪ Networking skills	▪ Ability to work under pressure ▪ Compliance ▪ Flexibility ▪ Motivation to learn ▪ Sustainable mindset
B	▪ Coding skills ▪ Process understanding ▪ State-of-the-art knowledge ▪ Technical skills	▪ Analytical skills ▪ Efficiency orientation	▪ Communication skills ▪ Networking skills ▪ Ability to work in a team	▪ Flexibility
C	▪ Coding skills ▪ Process understanding ▪ State-of-the-art knowledge ▪ Technical skills	▪ Analytical skills ▪ Creativity ▪ Efficiency orientation ▪ Problem-solving	-	▪ Flexibility
D	▪ Coding skills ▪ State-of-the-art knowledge ▪ Technical skills	▪ Analytical skills ▪ Efficiency orientation ▪ Problem-solving	▪ Communication skills ▪ Networking skills	-
E	▪ Media skills ▪ State-of-the-art knowledge ▪ Understanding IT security	▪ Creativity ▪ Problem-solving ▪ Analytical skills ▪ Efficiency orientation	▪ Ability to be compromising and co-operative ▪ Ability to work in a team ▪ Communication skills ▪ Networking skills	▪ Flexibility ▪ Sustainable mindset
F	▪ Coding skills ▪ Media skills ▪ State-of-the-art knowledge ▪ Technical skills ▪ Understanding IT security	▪ Analytical skills ▪ Creativity ▪ Efficiency orientation ▪ Entrepreneurial thinking ▪ Problem-solving	▪ Ability to work in a team ▪ Communication skills ▪ Leadership skills	▪ Ability to work under pressure
G	▪ Media skills ▪ State-of-the-art knowledge ▪ Technical skills ▪ Understanding IT security	▪ Analytical skills ▪ Creativity ▪ Efficiency orientation ▪ Problem-solving	▪ Ability to work in a team ▪ Communication skills ▪ Leadership skills	▪ Ability to work under pressure ▪ Ambiguity tolerance ▪ Flexibility
H	▪ Process understanding ▪ Technical skills	▪ Analytical skills ▪ Conflict solving ▪ Creativity ▪ Decision making ▪ Problem-solving	▪ Ability to transfer knowledge ▪ Communication skills ▪ Language skills	▪ Ambiguity tolerance ▪ Ability to work under pressure ▪ Compliance ▪ Flexibility