An investigation upon Industry 4.0 implementation: the case of small and medium enterprises and Lean organizations

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Beatrice Paiva Santos

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Dedication

To my family, my parents Humberto and Ana Maria, my sisters Solange and Alessandra, my husband Filipe, and my son Oliver.

Tudo vale a pena, quando a alma não é pequena.

Fernando Pessoa

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Resumo

Nos últimos anos, as indústrias têm passado por várias mudanças tanto nos seus sistemas operacionais, como de gestão. Juntamente com a inovação tecnológica e alta competitividade; as mudanças nas necessidades dos clientes levaram as indústrias a se concentrarem na produção de produtos altamente personalizados e com tempo de lançamento no mercado cade vez menores. Nesse contexto, a Indústria 4.0 é um paradigma de manufatura que promete ter um grande impacto não só na melhoria da produtividade, mas também no desenvolvimento de novos produtos, serviços e modelos de negócios.

No entanto, a revisão da literatura mostrou que a investigação sobre a implementação da Indústria 4.0 ainda é caracterizada por algumas lacunas (por exemplo em tópicos como a implementação da Indústria 4.0 em pequenas e médias empresas (PMEs) e sua integração com a filosofia de gestão *Lean Management*). Diante disso, esta tese procura responder à quatro questões-chave: (RQ1) Quais são os desafios e oportunidades para as PMEs no campo da Indústria 4.0? (RQ2) Quais são os recursos e capacidades necessários para a implementação da Indústria 4.0 nas PMEs? (RQ3) Como esses recursos e capacidades podem ser adquiridos e/ou desenvolvidos e (RQ4) Como integrar os paradigmas de manufatura, Indústria 4.0 e *Lean Management*?

Para responder à primeira questão de investigação, este trabalho empregou uma revisão semi-sistemática da literatura. O objetivo principal foi explorar a implementação da Indústria 4.0 nas PMEs, a fim de identificar quais são os desafios e oportunidades para as PMEs na era da Indústria 4.0.

Para fazer face à segunda e terceira questões de investigação, foi realizado um estudo de caso em 5 PMEs localizadas em Portugal a fim de atingir os seguintes objetivos: (1) identificar os recursos e capacidades necessários para implementar a Indústria 4.0 nas PME portuguesas; (2) esclarecer como essas PMEs adquirem e/ou desenvolvem esses recursos e capacidades. Além disso, com base nas teorias *resource-based view (RBV)* e *dynamic capabilities*, buscar evidências empíricas sobre como as PMEs usam recursos e capacidades para obter vantagem competitiva sustentável.

Finalmente, para lidar com a quarta questão de investigação, este estudo explorou a relação sinérgica entre a Indústria 4.0 e a filosofia de gestão Lean Management (LM) para identificar as principais tendências neste campo de investigação e promover as melhores práticas. A análise e discussão das melhores práticas revelaram um conjunto de potenciais relações, o que contribuiu para um entendimento mais claro sobre a integração da Indústria 4.0 com LM.

Palavras-chave

Industry 4.0; Smart Factory, Customização, *Lean Management*; Pequenas e Médias Empresas; *Resource-based View*; *Dynamic Capabilities*.

Abstract

In recent years, industries have undergone several shifts in their operating and management systems. Alongside to the technological innovation, rapid market changes and high competitiveness; growing customer needs are driving industries to focus on producing highly customized products with even less time to market. In this context, Industry 4.0 is a manufacturing paradigm that promises to have a great impact not only on improving productivity but also on developing new products, services and business models.

However, the literature review has shown that research on Industry 4.0 implementation is still characterized by some weaknesses and gaps (e.g., topics such as the implementation of Industry 4.0 in SMEs and its integration with Lean Management approach). Motivated by so, this thesis sought to answer four key questions: (RQ1) What are the challenges and opportunities for SMEs in the Industry 4.0 field? (RQ2) What are the resources and capabilities for Industry 4.0 implementation in SMEs? (RQ3) How can these resources and capabilities be acquired and/or developed and (RQ4) How to integrate Industry 4.0 and Lean Management?

To deal with the first research question, a semi-systematic literature review in the Industry 4.0 field was conducted. The main goal is to explore the implementation of Industry 4.0 in SMEs in order to identify common challenges and opportunities for SMEs in the Industry 4.0 era.

To face with the second and third research questions, a multiple case study research was conducted to pursue two main aims: (1) to identify the resources and capabilities required to implement Industry 4.0 in Portuguese SMEs. Furthermore, based on mainstream theories such as resource-based view (RBV) and dynamic capability theory, it sought empirical evidence on how SMEs use resources and capabilities to gain sustainable competitive advantage; (2) to shed light on how those SMEs acquire and/or develop the Industry 4.0 resources and capabilities.

Finally, this thesis employed a semi-systematic literature review methodology to deal with the fourth research question. As such, it explored the synergistic relationship between Industry 4.0 and Lean Management to identify the main trends in this field of research and, ultimately, the best practices. The analysis and discussion of the best practices revealed a set of potential relationships which provided a more clear understanding of the outcomes of an Industry 4.0-LM integration.

Keywords

Industry 4.0; Smart Factory; customization; Lean Management; Small and Medium Enterprises; Resource-based View; Dynamic Capabilities

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List of Acronyms

CPS	Cyber-Physical System
B2B	business to business
ERP	Enterprise Resource Planning
ICT	Information and Communication Technology
IoT	Internet of Things
LM	Lean Management
MRP	Material Requirement Planning
RBV	Resource-based view
SME	Small and Medium Enterprise
IT	Information Technology
USA	United States of America
IoS	Internet of Services
CAD	Computer Aided Design
SaaS	Software as a Service
PaaS	Platform as a Service
IaaS	Infrastructure as a Service
AR	Augmented Reality
VR	Virtual Reality
KPI	Key Performance Indicator
HMI	Human-Machine Interface
IWN	Industrial Wireless Network
M2M	Machine to Machine Communication
MES	Manufacturing Execution System
PLM	Product Lifecycle Management
PMEs	Pequenas e Médias Empresas
RFID	Radio-Frequency Identification
TPS	Toyota Production System
SLR	Systematic Literature Review
JIT	Just-in-Time
TQM	Total Quality Management
SCM	Supply Chain Management
VSM	Value Stream Mapping
TPM	Total Productive Maintenance
SMED	Single Minute Exchange of Die
VSM	Value Stream Mapping
TOC	Theory of Constraints
WIP	Work-in-Progress

Chapter 1. Introduction

This chapter presents the motivation for this thesis, aims, methodology, and thesis design.

1.1 Motivation

The evolution of information and communication technologies (ICT) and their introduction in manufacturing processes are transforming traditional industries, changing the way they are designed, and above all, managed (Piccarozzi *et al.*, 2018). In this context, Industry 4.0 is one of the major trends in recent years (Liao *et al.*, 2017; Culot *et al.*, 2020a). Considered by many authors and practitioners as the fourth industrial revolution (Bitkom *et al.*, 2016; Piccarozzi *et al.*, 2018), Industry 4.0 is one of the keywords used to describe a new paradigm shift that is based on the digitalization of factories (Chiarello *et al.*, 2018). The concept involves a set of new technologies such as cyber-physical systems (CPS), Internet of things (IoT), cloud computing and big data analytics, that aim to improve the transmission of information throughout the system, allowing decentralized decisions based on real-time data acquisition (Culot *et al.*, 2020a). In particular, three dimensions of changes are expected from this new development: technological change, social change and business paradigms change (Smit *et al.*, 2016).

The first ideas on Industry 4.0 were presented at the 2011 Hannover Fair as part of the Deutsch “High-Tech Strategy 2020 Action Plan” and aimed to act as a politically established target for strengthening Germany’s international competitive position in manufacturing (Kagermann *et al.*, 2013). Since then, the topic has been pointed out by academics, managers and policymakers (Bitkom *et al.*, 2016; Liao *et al.*, 2017; Schwab, 2018) as a critical mean to face contemporary challenges such as high competition, increasing demands for customized products and shorter product life cycles and lead times (Hu, 2013).

Nonetheless, although the popularity of Industry 4.0 has grown over the years and the topic is being presented in the literature as a highly beneficial manufacturing approach, it is well-known that its adoption by small and medium enterprises (SMEs) can be more challenging than by large enterprises (Mittal *et al.*, 2018a; Singh *et al.*, 2019). That is because Industry 4.0 relies on a vast scope of technologies and methodologies for which only a few companies have the necessary systems, competencies and capital (Oliff and Liu, 2017). Moreover, even though the concept appears to be more flexible and less expensive than previous digital approaches, such as Enterprise Resource Planning (ERP) and Material Requirement Planning (MRP), SMEs are often characterized by some weaknesses when it comes to managing complex computer solutions, due to their lack of expertise and fewer available resources to invest in new technologies than large companies (Mittal *et al.*, 2018a; Moeuf *et al.*, 2020). Thus, it would be expected that the approaches developed for large companies would not perfectly meet the specific needs of SMEs. Nevertheless, on the other hand, Industry 4.0 can be a great opportunity for SMEs to strengthen their market position and gain competitive advantage (Faller and Feldmüller, 2015). As a matter of fact, in Europe, nine out of ten enterprises are SMEs and two of three jobs are created by them (European Commission, 2020b). Thus, SMEs are considered the backbone of Europe's economy as they create jobs, drive economic growth and ensure social stability (European Commission, 2020b). Particularly, in Portugal, 99.9% of the companies are SMEs, which makes the investigation on this group of companies even more important (European Commission, 2019).

However, while on the one hand Industry 4.0 opens up new technological opportunities to the manufacturing companies, on the other hand it poses challenges, not only from the technical point of view but also from the organizational and management ones (Sanders *et al.*, 2016). The reason is because implementing Industry 4.0 will involve potentially radical changes across the firm, which includes its physical infrastructure, human resources, process management and manufacturing operations and technologies (Gilchrist, 2016).

In this regard, a subject that has been discussed in the literature is the integration of Industry 4.0 with other manufacturing approaches such as Lean Management (LM) (Buer *et al.*, 2018; Moeuf *et al.*, 2020). LM is considered a major manufacturing paradigm to create highly efficient processes since the early 1990s (Kolberg and Zühlke, 2015; Danese *et al.*, 2018). It concerns the strict integration of humans in the manufacturing process, continuous improvement, and focus on adding value to activities by avoiding wastes (Ohno, 1988; Mrugalska and Wyrwicka, 2017). Since its initial developments, LM has evolved so that its original set of hard tools (i.e., technical and analytical tools) have been complemented with soft practices (i.e., Lean practices related to people and relations such as small group problem solving, training, leadership, supplier partnerships, and customer involvement) (Shah and Ward, 2007; Bortolotti *et al.*, 2014; Martinez *et al.*, 2016; Costa *et al.*, 2019). This more human-centric approach allowed LM to be implemented to any process or context (Shah and

Ward, 2007). Consequently, LM enabled responses to market demands in many dimensions, such as product quality, faster delivery and lower costs, besides providing greater flexibility to meet customer requirements (Jadhav *et al.*, 2014; Ciano *et al.*, 2019). Furthermore, in light of the fact that LM is still considered the best practice in the automotive industry, as well as being even more present in other industry sectors, such as construction, services, food, medical, electrical and electronic equipment, ceramics, furniture, services, and so forth (Martinez *et al.*, 2016), implementing Industry 4.0 mostly means integrating technologies in companies that already operate according to LM principles (Buer *et al.*, 2018). In this context, Piccarozzi *et al.* (2018) add that the human factors and other soft elements of the organization – the core of Lean principles – are critical for a successful implementation of Industry 4.0. According to them, humans are involved in every technical or industrial system, whether it is operating the systems, developing new ideas, or as strategic decision-makers. So, taking the human element into account in a connected and complex system like Industry 4.0, is of crucial importance to ensure the system reliability and, consequently, the expected performance of firms (Kinzel, 2017; Piccarozzi *et al.*, 2018). In the past, many organizations have failed on their Lean journey because they focused on the isolated use of tools and techniques and neglected the human elements. (Costa *et al.*, 2019; Akmal *et al.*, 2020). This is probably due to the fact that the implementation of technical tools alone does not guarantee sustainable results in the long term. Although it is not entirely fair to generalize, since each company is different regarding its production system and/or its context of operation, this argument has been strongly defended within the literature (Bortolotti *et al.*, 2014; Costa *et al.*, 2019; Akmal *et al.*, 2020).

So far, much research in Industry 4.0 has focused on the development and validation of new technologies rather than providing paths and means of implementation (Moeuf *et al.*, 2018). Although this gap has been reduced in recent years, it still generates uncertainties about the necessary resources and capabilities to implement Industry 4.0 and, consequently, the appropriate strategies to acquire and/or develop them (Schumacher *et al.*, 2016). It becomes more real when it comes to the context of SMEs. In fact, even though the Industry 4.0 literature is starting to become a mature field, its requirements and implications are not yet clear to most SMEs (Sanders *et al.*, 2016; Moeuf *et al.*, 2018; Cimini *et al.*, 2020; Culot *et al.*, 2020a). In addition, as mentioned before, Industry 4.0 will affect the shop floor practices that are typically related to LM (Buer *et al.*, 2018). As such, the initial company situation must be taken into account in order to ensure the ability of the system to safely function. As Industry

4.0 is based on a number of technologies and tools that can be applied in different industries and contexts, applications may lead to contradictory performance results (Bai *et al.*, 2020). Thus, companies that have already applied LM need guidelines to help them deal with Industry 4.0 (Meudt *et al.*, 2017). Thus, a research that explores the sinergic relationship between these two approaches also deserve more attention (Brettel *et al.*, 2014; Tortorella and Fettermann, 2017; Buer *et al.*, 2018; Kamble *et al.*, 2019; Pagliosa and Tortorella, 2019).

Therefore, whereas some companies are eager to introduce new technologies to improve quality, efficiency and effectiveness, and their market competitiveness (Tassey, 2014), there is still a need for a deeper understanding of Industry 4.0 subject, in order to facilitate the transition to this new manufacturing approach. As such, this thesis draws attention to two distinct but interrelated topics within the Industry 4.0 research: the implementation of Industry 4.0 in SMEs and its integration with Lean Management approach.

1.2 Aims of the thesis

Current research on Industry 4.0 has focused on distinct topics, such as development of specific technological Industry 4.0 solutions (Helo *et al.*, 2014; Ren *et al.*, 2015; Cheng *et al.*, 2018); business models (Müller *et al.*, 2018; Safar *et al.*, 2018); Industry 4.0 maturity and readiness models (Ganzarain and Errasti, 2016; Mittal *et al.*, 2018b); the effects of Industry 4.0 on performance (Dalenogare *et al.*, 2018; Kamble *et al.*, 2019); and Industry 4.0 implementation (Frank *et al.*, 2019a; Mittal *et al.*, 2019; Moeuf *et al.*, 2020). While some of the abovementioned topics, such as the technological solutions, have been well studied, others, such as Industry 4.0 implementation, still needs to be further developed (Lee *et al.*, 2015; Moeuf *et al.*, 2018; Frank *et al.*, 2019a; Pagliosa and Tortorella, 2019). In fact, the literature review revealed that, despite the growing interest in this subject, it has not yet been fully presented. In this sense, the following four major gaps have been identified in the literature: (1) research on Industry 4.0 implementation is usually focused on large enterprises (i.e., neglecting that the management of SMEs is entirely different from the management of large enterprises) (Neirotti *et al.*, 2017; Mittal *et al.*, 2018a, 2019; Moeuf *et al.*, 2018, 2020); (2) the resources/capabilities required to implement Industry 4.0 in SMEs have not been fully exploited in current literature (e.g., research is not adequately grounded in mainstream theories such as resource-based view (RBV) and dynamic capability theory) (Neirotti *et al.*, 2017; Hasselblatt *et al.*, 2018); (3) there is a lack of evidence about how can SMEs acquire and/or develop resources and capabilities to implement Industry 4.0 (Neirotti *et* *al*., 2017; Hasselblatt *et al*., 2018; Mittal *et al*., 2018a; Moeuf *et al*., 2018; Moeuf *et al*., 2020); and (4) most research exploring the implementation of Industry 4.0 with LM is either theoretical or focused on very specific issues (e.g., it does not pay much attention to best practices regarding an Industry 4.0-LM integration) (Wagner *et al*., 2017; Powell *et al*., 2018; Pagliosa and Tortorella, 2019).

The aforementioned gaps were organized into four key questions (see Table 1). Thus, through the first research question *(RQ1) – what are the challenges and opportunities for SMEs in the Industry 4.0 field?* – this thesis aims to synthetize the existing literature in Industry 4.0 and identify common challenges and opportunities for SMEs in Industry 4.0 implementation. The second research question *(RQ2) – what are the resources and capabilities for Industry 4.0 implementation in SMEs?* – aims to identify the resources and capabilities required to implement Industry 4.0 in SMEs. Moreover, based on mainstream theories such as resource-based view (RBV) and dynamic capability theory, it seeks empirical evidence on how SMEs can use resources and capabilities to achieve sustainable competitive advantage. By the third research question *(RQ3) – how can these resources and capabilities be acquired and/or developed?* – the thesis aims to shed light on how SMEs acquire and/or develop the Industry 4.0 resources and capabilities needed. Finally, by addressing the fourth research question *(RQ4) – how to integrate Industry 4.0 and Lean Management?* – this thesis intends to identify real-world examples of Industry 4.0-LM integration in the extant body of knowledge in order to make explicit the best practices that have been implemented by distinct industrial sectors. The second and third research questions refer to the empirical part of the thesis.

Table 1. Research questions (RQ)

(RQ1)	*What are the challenges and opportunities for SMEs in the Industry 4.0 field?*
(RQ2)	*What are the resources and capabilities for Industry 4.0 implementation in SMEs?*
(RQ3)	*How can these resources and capabilities be acquired and/or developed?*
(RQ4)	*How to integrate Industry 4.0 and Lean Management?*

1.3 Methodology

This thesis adopts an inductive approach, as it allows to expand an existing theory and think the research problems in an ascending way. Specifically, the goal of an inductive research is to infer theoretical concepts and identify patterns from observed data (Bhattacherjee, 2012). In this sense, this thesis can also be classified as an exploratory research. Exploratory research is often used in new areas of inquiry, where the objectives are to provide a well-grounded picture of a particular phenomenon, and generate new ideas or test the feasibility of conducting a broader study of that phenomenon (Bhattacherjee, 2012). This type of research may not lead to definitive conclusions about the findings but may be valuable in scoping out the nature and extent of the problem, and serve as a precursor for future research. Moreover, because of its flexible character, it can address research questions of all types (e.g., what and how). The choice of this approach was, however, made due to two main reasons: (1) the focus on SMEs and (2) the nature of RQs. In addition, this thesis uses two different research methods to achieve its goals: a semi-systematic literature review and a multiple case study method. In general, a semi-systematic review or narrative review is a good strategy to study uncover areas where more research is needed and that have been conceptualized differently by diverse groups of researchers and within various disciplines (Wong *et al.*, 2013). This approach can be broader, like exploring the state of knowledge on a particular topic (e.g., Industry 4.0 implementaion in SMEs) or it can be narrow, like investigating the relationship between two specifc variables (e.g., Industry 4.0 and Lean Management). Thus, it can be used to provide an overview of a research subject, to identify research gaps within the literature, and to create research agendas. In addition, a semi-systematic review looks at how a research in a given field has been developed over time, highlighting the strengths and limitations of the respective research, which helps to understand complex areas like Industry 4.0 (Wong *et al.*, 2013). Nonetheless, despite covering broad matters, the research process must be transparent in order to allow readers to evaluate whether the arguments presented are reasonable (Snyder, 2019). On the other hand, case study method is preferred in examining contemporary events within their real-life context and when the boundaries between phenomenon and context are unclear (Yin, 2009). As the implementation of Industry 4.0 in SMEs is a contemporary and still evolving topic, a case study design is the best method to be used, since it allows to generate valid and generalizable results (Gibbert *et al.*, 2008). Moreover, in order to increase both the robustness and the generalizability of the results, this thesis conducted a multiple case study in five SMEs instead of relying on a single study (Chiang and Lee, 2017; J. Müller *et al.*, 2017). Finally, because of these characteristics, case studies have been a common research strategy in many areas, such as psychology, sociology, political science, as well as in business and management disciplines (Eisenhardt, 1989; Voss *et al.*, 2002; Yin, 2009). Figure 1 illustrates the adopted research methodology described above.

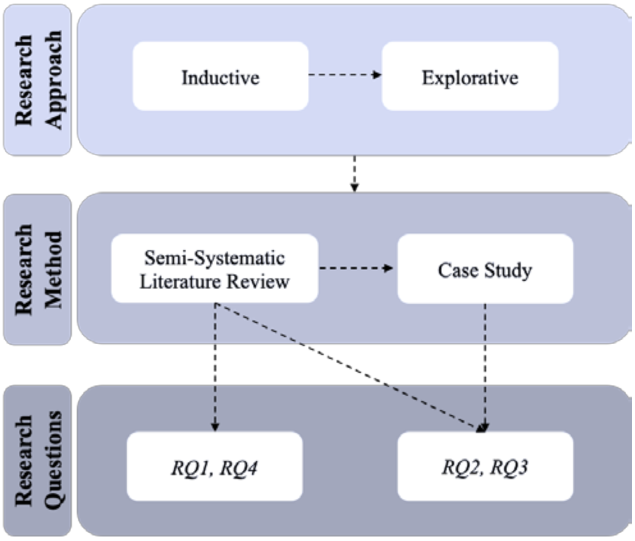

Figure 1. Methodology of the thesis

1.4 Thesis design

This thesis is based on three scientific papers in order to answer to the four above-mentioned research questions (see section 1.2).

Chapter 2 is adapted from the book chapter, Santos B.P., Charrua Santos F.M.B., Lima T.D.M. (2019), Challenges and Opportunities Towards an Industry 4.0 Production. *In: Ao SI., Gelman L., Kim H. (eds) Transactions on Engineering Technologies. WCE 2018*. Springer, Singapore. As such, it addresses the *RQ1* by conducting a semi-systematic literature review in the Industry 4.0 field. More specifically, it introduces Industry 4.0 by presenting its origins, conceptual definitions, related elements, challenges and opportunities, and highlighting its relevance for research and practice. Finally, it exploits the implementation of Industry 4.0 in SMEs in order to identify challenges and opportunities for SMEs in the Industry 4.0 era. In doing so, it withdraws from the existing literature a set of 16 common challenges faced by SMEs and provide suggestions for overcoming these challenges that can be seen as opportunities for SMEs looking to survive the fourth industrial revolution.

Chapter 3 is based on the paper, Santos, B., Dieste, M., Orzes, G. and Charrua-Santos, F. (2022), Resources and capabilities for Industry 4.0 implementation: evidence from proactive Portuguese SMEs, *Journal of Manufacturing Technology Management*. The paper addresses the RQ2 and RQ3 by conducting a multiple case study analysis in five Portuguese SMEs from three different sectors (automotive, automation and textile). In the literature, there is a general consensus that suggests that 4-10 case studies can provide credible explanations as well as the generalization of the results (Curtis *et al.*, 2000; Jaca *et al.*, 2014; Dieste *et al.*, 2020). Therefore, this chapter seeks to shed light on the resources and capabilities required by SMEs to successfully implement Industry 4.0 and exploit how these resources and capabilities can be acquired and/or developed by them. In doing so, it provides a list of 33 resources and capabilities to implement Industry 4.0 in SMEs. In addition, drawn onto two major strategic management theories, i.e., resource-based view (RBV) and dynamic capability theory, the study highlights how SMEs use resources/capabilities to achieve sustainable competitive advantage. More in detail, this study is among the first studies to carry out an analysis of the resources and capabilities for Industry 4.0 implementation in SMEs through the lens of RBV and the dynamic capability theory.

Chapter 4, adapted from the paper Beatrice Paiva Santos, Daisy Valle Enrique, Vinicius B.P. Maciel, Tânia Miranda Lima, Fernando Charrua-Santos, Renata Walczak (2021), The Synergic Relationship Between Industry 4.0 and Lean Management: Best Practices from the Literature. *Management and Production Engineering Review*, vol. 12, no. 1, pp. 1-14, addresses the *RQ4* by conducting a semi-systematic literature review in the intersecting fields of Industry 4.0 and LM. As such, it first summarizes the literature on Lean Management, highlighting their foundations, concepts, and main applications. Second, it explores the synergistic relationship between these two manufacturing approaches to identify the main trends in this field of research and, ultimately, the best practices. Designed as a review paper (Paré *et al.*, 2015), this chapter aims to intensify the discussion about how to integrate Industry 4.0 with Lean Management by presenting and discussing 6 real-world examples of an Industry 4.0-LM integration.

Chapter 5 presents the synopsis, contributions to theory and practice, the major limitations of the thesis and the future research directions.

Chapter 2. Literature Review

This chapter presents a literature review on Industry 4.0 topic. More in detail, it presents the purpose of the chapter, the literature review approach, Industry 4.0 background, Industry 4.0 defitition, Industry 4.0 technologies, key features of Industry 4.0, outcomes and challenges, Industry 4.0 in SMEs, and conclusions and future research directions.

2.1 Purpose

The aim of this chapter is to conduct a semi-systematic literature review (Snyder, 2019) on Industry 4.0 topic. More in detail: (1) to collect and synthetize the existing literature on Industry 4.0 field; and (2) to address *RQ1*, i.e., *what are the challenges and opportunities for SMEs in the Industry 4.0 field?* (see section 1.2); identifying common challenges and opportunities for the implementation of Industry 4.0 in SMEs.

2.2 Literature review approach

Traditionally, a literature review attempts to identify what has been written on a given subject in order to provide a broad and comprehensive understanding of the current state of knowledge in a particular area (Paré *et al.*, 2015; Savaget *et al.*, 2019). In general, it provides the theoretical foundations and context of the research question, thereby acting as an important starting point in the research processes (Baker *et al.*, 2000). Moreover, a literature review is generally seen as an useful educational study for both, scholars and practitioners, as it often tends to be more up-to-date than textbooks (Green *et al.*, 2006). According to Paré et al. (2015), to carry out an effective and methodologically sound literature review it is essential to advance the knowledge and understand the breadth of the research on a topic of interest, synthesise the empirical evidence, develop theories or provide a conceptual background for subsequent research, as well as to identify the topics or research domains that require further study. In other words, a comprehensive review of the literature serves to understand all potentially relevant research traditions in a given field and, thus, reveal which issues will require further attention (Snyder, 2019).

As such, to assess the state of Industry 4.0 research, two different methodological techniques were employed. Following Geissdoerfer et al. (2017) and Savaget et al. (2019), the review started with an initial sample of papers published by Scopus database, the largest abstract and citation database of peer-reviewed literature, and then was followed by snowballing approach to expand the literature and compose a pre-final sample. As Industry 4.0 is still emerging and rapidly evolving, the snowballing approach seemed to be appropriate, as this technique allows the researcher to keep up with both established and emerging trends (Culot *et al.*, 2020a). In addition, to ensure valid and replicable results, this literature review uses a transparent process for inclusion and exclusion of papers that helped to identify the sample of papers that would be initially investigated.

Data were first collected by searching with the keywords “Industry 4.0” OR “Smart Manufacturing”. Keywords referring to other labels of the phenomenon and specific technologies such as “Internet of Things”, “3D printing” and so forth were not included in the search, since it was assumed that those two keywords would cover a significant number of publications. The search was limited to peer-reviewed papers, written in English and with a time frame from 2011 (the year in which Industry 4.0 were first presented by the German government) to september 2017 (the period of the research). This time frame was updated in January of 2021. The result of this initial procedure was 2.071 publications. Titles and abstracts of these publications were then analyzed by using the following inclusion/exclusion criteria. Papers published in the most influential journals in the Industry 4.0 field that provided a comprehensive characterization of Industry 4.0 and addressed its implementation in SMEs were included in the sample, and papers that referred to specific technical solutions were excluded. Thus, the full content of 107 papers were examined. At this stage, 68 papers were eligible to compose the initial sample. Hereafter, the snowballing methodology was employed (see Figure 2).

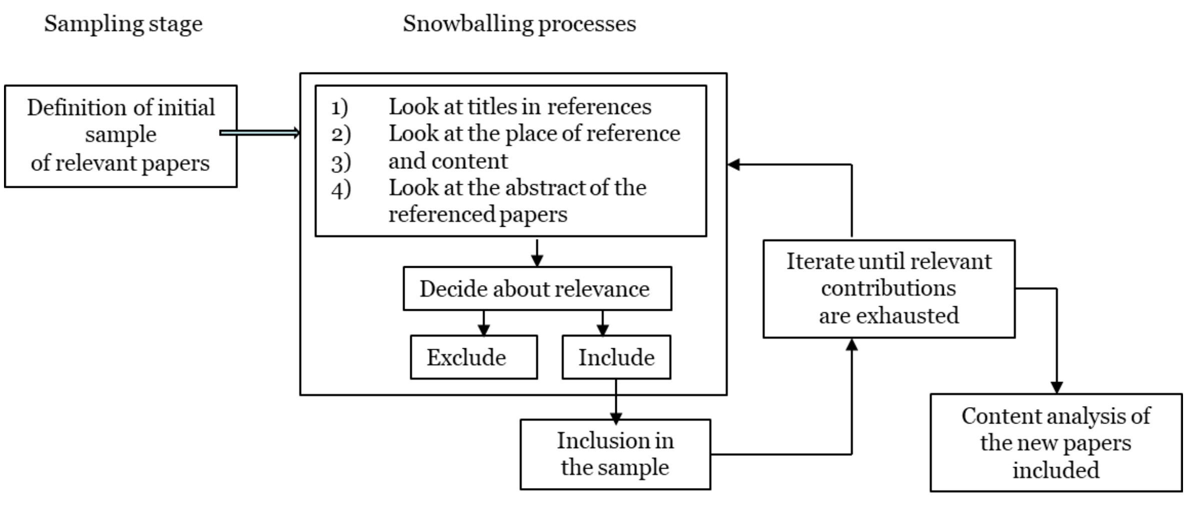

Figure 2. Snowballing process (adapted from Geissdoerfer et al., 2017; Savaget et al., 2019)

The snowballing approach refers to the iterative procedure used to expand the coverage of the literature by scanning the references of the reviewed papers. In this procedure, the iterative processes are repeated several times until the relevant contributions are exhausted. The inclusion/exclusion criteria used in this stage had some variation in relation to those adopted in the sampling stage. Here, again, references were considered relevant when they contributed with new insights in terms of the foundations of the concept and its implementation in SMEs. In addition, because *RQ2* and *RQ3* are focused on Industry 4.0 resources/capabilities, publications that focus on mainstream theories in this area such as RBV and dynamic capability theory have also been included. In this sense, considering there is much information that is not holded by the scientific literature, grey literature (e.g., conference proceedings, government reports and consultancy reports) was also elegible to be included. In fact, for emerging topics such as Industry 4.0, grey literature can represent a valuable contribution, as it helps to identify more recent developments, and can also limit publication bias (Scargle, 2000). It enabled a selection of 94 papers as a pre-final sample.

This methodology, however, reveals some limitations. First, the initial sample of papers was defined in 2017, when this research project started. In that case, the snowballing approach addressed only publications prior to 2017. However, it should be noted that Industry 4.0 is still evolving and therefore research on this topic is still being developed. This means that in the past three years, a great deal of relevant research on the topic has been produced. Thus, to ensure that all relevant publications were examined, papers included in recent literature reviews on Industry 4.0 were considered (e.g., Mittal *et al.*, 2018a; Piccarozzi *et al.*, 2018; Pagliosa and Tortorella, 2019; Oztemel and Gursev, 2020). At this stage, the selection of publications (inclusion/exclusion criteria) was made based on suggestions from experts in the field and from scientific websites (eg., ResearchGate, Academia.edu). Moreover, for each new publication read, the snowballing approach was used again. This adaptation on the review strategy was of significant help in ensuring that the appropriate literature was accurately covered in order to answer the research questions (Snyder, 2019). Therefore, the final sample of this literature review is composed of 141 publications.

2.3 Industry 4.0 background

The industrial sector has always been crucial to the economic development of countries. As such, in the last three centuries, industries have undergone massive changes and have witnessed the evolution of manufacturing techniques from artisanal production of the 19th century, to mass production of the 20th century, to the current trend of mass customization (Rüttimann and Stöckli, 2016).

Looking back, the first industrial revolution, that occurred between 1760 and 1840, was marked by the transition from manual labor to steam powered machines. In the end of the 19th century, the utilization of electricity in industrial processes, the mass production and the division of labor, characterized the second industrial revolution. Starting in the 70's, the third industrial revolution, was defined by the use of electronics and information technologies (IT) to support further automation (Bitkom *et al.*, 2016). Following these events, more recently, new developments in manufacturing processes have led to the definition of the fourth industrial revolution, also known as "Industry 4.0" (Piccarozzi *et al.*, 2018). Basically, it consists in a very broad and complex domain that aims to build smart factories by using communication, information and intelligent technologies in order to enable the mass production of highly customized products (Kagermann *et al.*, 2013; Kiel *et al.*, 2017). Nonetheless, despite Industry 4.0 is being referred to as the next era of manufacturing, some authors see it as a natural evolution of its predecessor, the third industrial revolution, relying on the developments from this earlier stage of industrialization (Lasi *et al.*, 2014; Maynard, 2015). According to Lasi *et al.* (2014), the implementation of IT in the manufacturing industry in the 70's initiated a widespread wave of digitalization, creating a suitable environment for Industry 4.0. Figure 3 illustrates the four industrial revolutions.

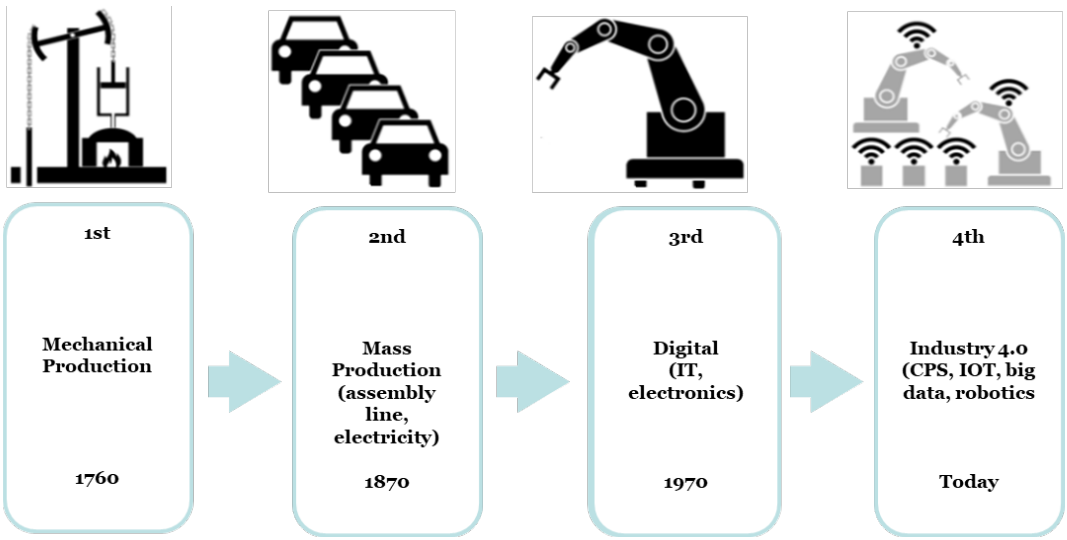

Figure 3. Industrial Revolutions

In effect, the term Industry 4.0 was first presented in 2011, at the Hanover Fair, in Germany, and it aimed to cover two distinct meanings: a synonym for a fourth industrial revolution and a label for the long-term strategy pursued by the German government – "High-Tech Strategy 2020 Action Plan" – to strengthening the competitiveness of its industry (Kagermann *et al.*, 2013). Since then, the German government has institutionalized its commitment to industry in creating a platform led by Ministries of Economics and business, science and trade representatives (Hermann *et al.*, 2016). Afterwards, expectations about this new technology-driven paradigm increased around the world, making the German initiative of applying disruptive ICT technologies in the manufacturing environment easily adopted by the European Union in its H2020 program (European Commission, 2017). Similar initiatives were also adopted by other geographies, such as, "Industrial Internet", in the United States of America (USA) and "Internet +", in China (Smit *et al.*, 2016).

2.4 Defining Industry 4.0

Industry 4.0 emerges from the overlapping of several technological developments involving products and processes. However, even though the topic has been a subject of intense discussion over the years, it seems that governments, scholars and practitioners have different opinions about the elements that compose Industry 4.0, how these elements are related and even more important, where Industry 4.0 might be applicable (Buer *et al.*, 2018; Chiarello *et al.*, 2018). So, it is not a surprise that recent studies have found more than 100 different definitions of the topic, but no general consensus has been reached on the definition of the term (Hermann *et al.*, 2016; Hofmann and Rüsch, 2017; Moeuf *et al.*, 2018). The consequences were the emergence of definitions from the most diverse perspectives. In this regards, through a literature review on Industry 4.0 in management studies, Piccarozzi *et al.* (2018) have found six different categories of definitions. The following domains were classified based on the context in which they were found and the results encompass: technical definitions/components; value chain; smart factory; competitiveness; strategy and internet of things. For example, Hermann *et al.* (2016), provide a definition focused on the vision of smart factory and in order to improve the understanding of the concept, introduce and describe some key components that makes it possible to achieve the Industry 4.0 vision. According to them, Industry 4.0 is:

"*a collective term for technologies and concepts of value chain organization. Within the modular structured smart factories of Industry 4.0, CPS monitor physical processes, create a virtual copy of the physical world and make decentralized* *decisions. Over the IoT, CPS communicate and cooperate with each other and humans in real-time. Via the Internet of Services (IoS), both internal and cross-organizational services are offered and utilized by participants of the value chain*" (Hermann *et al.*, (2016, p.11).

On the other hand, adopting a more holistic view, Buer *et al.* (2018), present the Industry 4.0 phenomenon as:

"*the usage of intelligent products and processes, which enables autonomous data collection and analysis as well as interaction between products, processes, suppliers, and customers through the internet*" (Buer *et al.*, 2018, p.4).

Aside the distinct issues, concepts and/or tools used in these definitions, other authors adopted different terms to represent the next era of manufacturing (Piccarozzi *et al.*, 2018). "Smart Manufacturing", "Fourth Industrial Revolution" and "Industrial Internet of Things (IIoT)" represent just a few of the labels that are often used as synonyms for Industry 4.0 (Culot *et al.*, 2020a). Some interesting examples are given by Kang (2016) who states that Smart Manufacturing is:

"*the fourth revolution in the manufacturing industry and is also considered as a new paradigm, is the collection of cutting-edge technologies that support effective and accurate engineering decision-making in real-time through the introduction of various ICT technologies and the convergence with the existing manufacturing technologies*" (Kang, 2016, p.14)

and Kiel *et al.* (2017) who claim that IIoT is:

"a synonym for the German term "Industry 4.0" and defined it as "*the integration of IoT technologies into industrial production, which results in the digitized connection of industrial value creation*" (Kiel *et al.*, 2017, p.3).

In fact, a lack of a clear definition may lead difficulties of communication among researchers, as well as hamper the understanding and/or implementation of Industry 4.0 by practitioners (Buer *et al.*, 2018; Piccarozzi *et al.*, 2018). Therefore, in order to ensure validity and avoid including inappropriate issues in our analysis, it seems important to find a definition that meets the goals of this thesis and on which it will be developed. As such, we rely on Kagermann *et al.* (2013), who defined the vision of Industry 4.0 as:

“a new level of sociotechnical interaction between all the actors and resources involved in manufacturing. This will revolve around networks of manufacturing resources (manufacturing machinery, robots, conveyor and warehousing systems and production facilities) that are autonomous, capable of controlling themselves in response to different situations, self-configuring, knowledge-based, sensor-equipped and spatially dispersed and that also incorporate the relevant planning and management systems” (Kagermann *et al.*, 2013, p.20).

This definition considers some technological aspects of the innovations introduced with Industry 4.0, but also take into account the managerial ones (Hermann *et al.*, 2016; Müller *et al.*, 2018; Piccarozzi *et al.*, 2018; Moeuf *et al.*, 2020). Other authors, embracing a similar approach, argued that Industry 4.0 should represent a managerial strategy (Johansson *et al.*, 2017; Moeuf *et al.*, 2020). The reason why these authors put strategy at the center of Industry 4.0 definition is because for any industry there are some challenges related to the effective acceptance and implementation of those technologies and, therefore, their integration can only be realized if a correct strategy has been formulated and implemented (Piccarozzi *et al.*, 2018; Závadská and Závadský, 2020). In other words, if along with technological choices the company does not define the right strategy, individuals will not simply adapt to the new approach and the company will not be able to make profit from it. Thus, following Piccarozzi *et al.*, (2018) we claim that a more comprehensive definition of Industry 4.0 should express the role of strategy while consider all aspects of the organization, from the technological and operational aspects of manufacturing to the human ones (Piccarozzi *et al.*, 2018).

2.5 Industry 4.0 technologies

The fourth wave of technological advances, known as Industry 4.0, is powered by a set of emerging technologies that are still evolving driven by the rapid growth and market uncertainty (Chiarello *et al.*, 2018; Dalenogare *et al.*, 2018).

In this context, if on the one hand the literature appears to have an agreement on key enabling technologies such as advanced robots, CPS, IoT, cloud computing and big data analytics (Piccarozzi *et al.*, 2018; Kamble *et al.*, 2019; Koh *et al.*, 2019), on the other hand, there is still no consensus on which other technologies should be part of the scope of Industry 4.0. For example, technologies such as computer aided design (CAD), ERP and MES, that were trends in the 1990’s, now are being called “old technologies” for some scholars. In the same vein, the additive manufacturing technologies (e.g., 3D printing) that became very popular at the beginning of the Industry 4.0 era, seem to have lost some visibility over the years, although they are still important (Culot *et al.*, 2020a). Meanwhile, technologies such as blockchain and 5G are gaining a lot of attention (Hofmann and Rüsch, 2017; Koh *et al.*, 2019).

So, it is not surprising that studies on Industry 4.0 have shown distinct sets of technologies as well as other technological elements that comprise the phenomenon (Boston Consulting Group [BCG], 2015; Tortorella and Fettermann, 2017; Dalenogare *et al.*, 2018; Frank *et al.*, 2019; Koh *et al.*, 2019; Culot *et al.*, 2020a). In 2015, the Boston Consulting Group presented nine technological advances that, according to them, constitute the pillars of Industry 4.0 (BCG, 2015). The model presented comprises big data and analytics, augmented reality, additive manufacturing, cloud computing, cybersecurity, IoT, horizontal and vertical integration, simulation and autonomous robots. In the same vein, Santos *et al.* (2018), introduced a conceptual framework where CPSs are the bases of Industry 4.0, while IoT and humans are at the heart of the transformation. IoT connecting all entities of the system and empowered humans ensuring that everything is running smoothly. The framework also comprises other key Industry 4.0 components as shown in Figure 4.

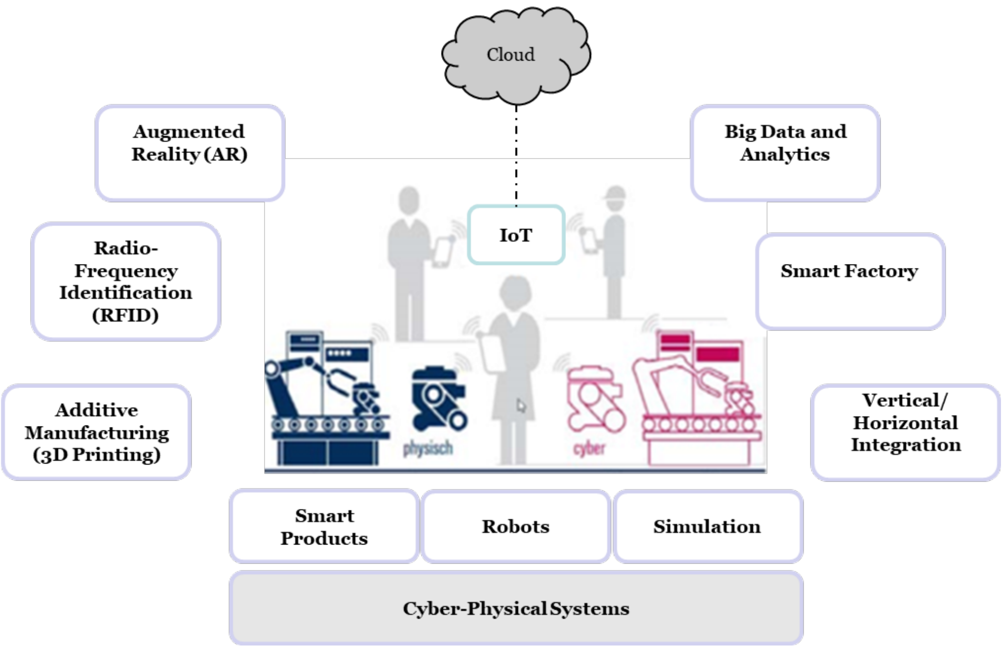

Figure 4. Industry 4.0 related technologies (Santos *et al.*, 2018)

Other studies, however, have addressed the issue by proposing different methodologies. Frank *et al.* (2019), adopted a managerial-oriented approach to develop a framework with two categories of technologies called “front-end” and “base” technologies. According to them, the “front-end” category comprises four dimensions that represents the transformation of manufacturing activities, such as “smart manufacturing”, “smart products”, “smart supply chain” and “smart working”. On the other hand, the “base” technologies (Internet of Things (IoT), cloud services, big data and analytics) will support all dimensions of the “front-end” technologies, in order to form a fully integrated system (Frank *et al.*, 2019a). Culot *et al.* (2020a), in turn, suggested a categorization based on the nature of the technological innovations. In doing so, the authors categorized Industry 4.0 technologies into physical technologies, that should include sensors and additive manufacturing, for example, and digital technologies such as cloud computing and big data (Culot *et al.*, 2020a).

Additionally, depending on the field of application, a given technology can be described from different perspectives (Kagermann *et al.* 2013; Chiarello *et al.*, 2018). For example, in the literature, it is possible to find technologies developed for a specific domain/sector/business and technologies that have a general purpose and, therefore, can be explored in different areas (Chiarello *et al.*, 2018). A good example is given by the Radio-Frequency Identification (RFID) technology. RFID is an automatic identification technology that identify and track tags linked or incorporated into objects (Aydos and Ferreira, 2016). This technology has been used since 1999 and can be considered as an early example of CPS (Smit *et al.*, 2016). In practice, RFID can be applied for different goals such as identification, safety and tracking as well as in different areas of manufacturing (e.g., logistics, production, maintenance). It means that each application of a given technology is able to develop the basic technology in a variety of directions, which makes the scope of technologies related to Industry 4.0 even more vast and heterogeneous (Aydos and Ferreira, 2016; Chiarello *et al.*, 2018). Some relevant technologies are described below.

2.5.1 Cyber-Physical System (CPS)

CPS uses sensors, computers and networks to allow different components to interact and communicate with each other, making it possible to merge the virtual and physical worlds (Tsai and Lai, 2018). By integrating CPS in production, logistics and services, companies can achieve the goal of resilient and self-adaptive systems that can intelligently adjust to differents production patterns (Lee *et al.*, 2015). However, since the full integration of CPS in manufacturing requires further understanding, a five level model has been used in order to provide guidelines and methodologies for its implementation (Petrillo *et al.*, 2018; Tsai and Lai, 2018). In this sense, the so-called

5C architecture deconstructs CPS into five levels of functionality such as: connection, conversion, cyber, cognition and configuration (Lee *et al.*, 2015).

(1) *Smart connection:* The first step to develop a CPS application is to acquire accurate and reliable data from machines and their components. This data can be directly measured by sensors or acquired the company's IT systems such as ERP, MES, SCM and so on.

(2) *Data* to information conversion: The data collected has to be transformed into useful information. Thus, smart analytics (e.g., big data analytics) must be used for prognostics and health management applications as well to bring self-awareness to machines.

(3) *Cyber:* The cyber level is considered to be the most important in the 5C architecture as it plays the role of a central information hub. As information from each machine in the network is being pushed to it, which means a massive amount of information, specific analytics are needed to extract additional information about the status of an individual machine in the fleet. With the creation of a digital twin, machines gain the ability to self-compare, enabling the prediction of future machine behaviors.

(4) *Cognition:* At this level, the monitored system provides knowledge to support expert users to make the right decisions. As such, the use of infographics is necessary to present the acquired knowledge to them. Moreover, the comparative information and individual machine status can support decision on priority of tasks to optimize the maintaining process.

(5) *Configuration:* Through feedbacks from the cyber level, the configuration level acts as a supervisory control system that allows the machine to be self-configured and self-adaptive. Therefore, it is possible to apply the corrective and preventive decisions that were taken at the cognition level.

2.5.2 Internet of Things (IoT)

The Internet of Things (IoT) is the inter-networking of “things” and “objects” that are embedded with electronic sensors, RFID, actuators and other digital devices in order to collect and exchange data (Zhong *et al.*, 2017; Oztemel and Gursev, 2020). Considering that “things” and “objects” can be also understood as CPS, IoT can be defined as the network in which CPS interact and cooperate with each other (Hermann *et al.*, 2016). In other words, IoT is the digital integration of physical objects, systems and services which makes it possible to monitor and manage a network intelligently (Smit *et al.*, 2016). Kiel *et al.* (2017) add that IoT can also be exploited in terms of strategic differentiation and competitive advantages. For example, IoT enables enhanced relationships with customers similar to those of partners. By offering more flexible and personalized value proposals, with less complexity, customer satisfaction and retention are enhanced.

2.5.3 Biga data

Big data refers to datasets that are characterized by their high volume (i.e., the large amount of data), variety (i.e., data comes from different sources and it is generated in different forms), velocity (i.e., data is processed at high speed), veracity (i.e., the uncertainty of data), and value (i.e., the value hidden in the data) (Beyer and Douglas, 2012; Tao *et al.*, 2018). Because of these characteristics specific technologies and new analytical tools are required for efficient data storage, management, and analysis (Mittal *et al.*, 2018a). Thus, by transforming big volumes of data in meaningful information, big data analytics allows better decision-making, process optimization, improved quality, and save energy, improving overall manufacturing efficiency (Bahrin *et al.*, 2016; Lidong and Guanghui, 2016). For example, big data analytics can help CPSs to reach the goal of intelligent, resilient, and self-adaptable systems through smart prognostics and diagnostics as it enables the collection and analysis of data from many different sources such as machines, networked sensors, and systems (Lee *et al.*, 2015).

2.5.4 Cloud computing

Cloud computing refers to a delivery service model — that includes servers, databases, storage, networks, and applications — in which virtualized and scalable resources are provided over the Internet (“the cloud”) (Helo *et al.*, 2014; Zhong *et al.*, 2017). It is called “cloud” because information is found remotely in the virtual space, allowing users (e.g., customers and employees) to access data from anywhere and at any time (Oztemel and Gursev, 2020). The main benefit for companies is that cloud solutions can be adopted with a minimum budget as it requires almost no investment in internal IT resources, such as hardware, software, and IT experts (Xu, 2012). Thus, cloud computing reduces operating costs, eliminate infrastructure complexity, increase speed and efficiency, protects data, and provides greater economies of scale. Moreover, it comprises three types of service models (e.g., software as a service (SaaS), platform as a service (PaaS), and infrastructure as a service (IaaS)) and four main types (e.g., public cloud, private cloud, community cloud, and hybrid cloud) (Mell and Grance, 2011). In Industry 4.0 environments, for example, cloud-based solutions can help companies to handle the big data, since it can provide scalable computing power to perform data analysis (Oztemel and Gursev, 2020).

2.5.5 Augmented reality

Augmented technology (AR) refers to any technology that "augments" the real-world environment of the user with digital information and media (e.g., sound, video, graphics, etc.) and that can be overlaid in real-time in her/his field of view (e.g., through smart phones, tablets, and smart glasses) (Wu *et al.*, 2013; Romero *et al.*, 2016). According to Azuma (1997), AR systems encompass three main characteristics: the combination of real and virtual worlds, real-time interaction, and the accurate 3D registration of virtual and real objects. Unlike virtual reality (VR) — that complete replaces the reality with a simulated one — AR alters the reality, integrating and adding value to the user's interaction with the real-world (Gartner IT Glossary, 2019). As such, AR can offer several advantages such as traceability, reduced failure rate, reliability, and faster cycle times (Romero *et al.*, 2016). In particular, AR can support employees in selecting parts from a warehouse or sending repair instructions on mobile devices, thus becoming a digital assistance system for reducing errors (Bahrin *et al.*, 2016). Moreover, AR can incorporate a new human-machine interface (HMI) for manufacturing IT applications and assets, displaying production KPIs (Key Performance Indicators) and providing real-time feedback on processes and machines to improve decision-making (Gorecky *et al.*, 2014).

2.5.6 Additive manufacturing

Additive manufacturing (AM), commonly known as 3D printing, refers to a set of technologies that create products from 3D data by adding layer-by-layer materials in contrast to traditional subtractive manufacturing methodologies (ASTM International, 2012). AM is considered a disruptive technology with a wide range of practical applications such as product prototyping, product development, 3D visualization, among others (Mellor *et al.*, 2014; Song *et al.*, 2015). Because this technology is insensitive to quantity and complexity, it brings benefits in terms of volume, time and costs, as well as greater flexibility in design and product customization than traditional manufacturing. AM technology also promotes competitive and sustainable local manufacturing. The shift from centralized and large-scale production to more local production enabled by AM, favors remote or undeveloped regions, since it reduces their dependence on skilled workforce (Jiang *et al.*, 2017). In addition, local and decentralized production reduces transport distances, eliminating the need of stocks and improving logistics (Bahrin *et al.*, 2016; Jiang *et al.*, 2017).

2.6 Key features of Industry 4.0

The main goal of Industry 4.0 is to create smart products, procedures and processes (Kagermann *et al.*, 2013). In doing so, Industry 4.0 allows flexible manufacturing and the analysis of a large amount of data in real time that will improve strategic and operational decision-making (Kagermann *et al.*, 2013). The principles that underpin the concept are interoperability, virtualization, decentralization, real-time capability, service orientation and modularity (Hermann *et al.*, 2016; Oztemel and Gursev, 2020). These principles are briefly described as follows:

- *Interoperability*: is achieved through CPS and it means that all CPS in the smart factory (machines, assembly lines and products) are able to communicate with each other and with humans over the IoT.
- *Virtualization:*. the data collected from sensors allocated in various parts of the factory allows physical processes to be monitored through the creation of a copy of the physical world into the virtual world.
- *Decentralization:* it refers to the ability of CPS to make autonomous decisions, since the growing demand for customized products makes it difficult do control systems centrally. Hereby, only in cases of failures tasks are delegated to a higher level.
- *Real-time capability:* it means that data is collected and analized in real time. In the smart factory it allows systems to rapid react and adapt to changes
- *Service orientation:* it enables services, CPS and humans to be available over the internet and therefore to be used by other participants of the value chain. As such, services can be offered internally and across company borders.
- *Modularity:* it refers to the ability of smart factories to flexibly adapt to changing requirements by expanding or replacing individual modules. For example, in case of changes in products characteristics or seasonal fluctuations.

Moreover, according to Kagermann *et al.*, (2013), the vision of Industry 4.0 revolves around four main factors: smart factory, smart products, customers and new business models.

Smart factory is a key Industry 4.0 solution that is highly flexible and reconfigurable and therefore capable of meeting complex market requirements, such as the growing individualism of customer requirements. In the smart factory, it is possible to move from a centralized production model to a decentralized one, where every manufacturing resource (e.g., sensors, actuators, conveyors, machines, robots, IT systems and human beings) is connected through a digital value chain *(*Kagermann *et al.*, 2013). These connected systems, also known as cyber-physical systems (CPS), can communicate and interact one to each other by using internet protocols such as Internet of Things (IoT) and analyze data from multiple sources to predict failures, optimize operations, adapt to changes and manufacture higher quality goods with reduced costs (BCG, 2015). Within the smart factory, physical prototypes become less important. The large amount of data collected by those systems allows virtual models to be built and updated with information from physical processes, increasing the importance of simulation approaches to support decision-making processes (Esmaeilian *et al.*, 2016).

Smart products identified through RFID tags provide relevant information about their location, history, status, and routes. These information allow workstations to "know" which manufacturing steps are being performed for each product and self-configuring to perform a specific task. The idea of the smart product concept is to expand the role of the workpiece, transforming it from a passive part into an active part of the system, which is a prerequisite to run the Industry 4.0 systems (Weyer *et al.*, 2015).

Customers are a key factor for any business and the improved communication along the whole value chain enabled by Industry 4.0 technologies certainly brings several advantages for them (Kagermann *et al.*, 2013). For instance, technologies embedded in the final products can provide data feedback to the development of new products, allowing new services for customers as well as an enhanced customer's experience (Zhong *et al.*, 2017; Frank *et al.*, 2019b).

This, in turn, has lead to the emergence of ***new business models*** that seek to better meet customers' needs while creating new opportunities for organizations (Zhong *et al.*, 2017; Culot *et al.*, 2020a). Müller *et al.* (2018) point out that the business model concept is directly linked to the exploitation of opportunities, such as the opportunities that arose with the new tecnologies. The authors explain that the business model concept refers to the way that organizations use to provide value to their customers, which includes their interaction with partners, suppliers and customers. In such sense, a trend that has long been discussed in the literature is servitization (Müller *et al.*, 2018; Frank *et al.*, 2019b). It represents a paradigm shift in the conventional model focused on goods and ownership to a service-oriented model (Müller *et al.*, 2018; Frank *et al.*, 2019b). Good examples are given by the new digital platforms. They enable closer relationships between manufacturing companies and technology and service providers, facilitating access to the resources and capabilities they need, as well as sharing economic practices (Culot *et al.*, 2020a). Some worthwile examples are digital platforms such as Google, Amazon, Facebook, Uber, Airbnb, among others. These examples show how companies can innovate and profit by offering not only goods, but also content and services to their users. Thereby, Industry 4.0 changes the competitiveness of companies and countries, which brings greater opportunities for business growth (BCG, 2015).

The logic underlying this industrial transformation involves three types of integration: horizontal integration, vertical integration, and end-to-end engineering integration (Hermann *et al.*, 2016; Smit *et al.*, 2016; Mrugalska and Wyrwicka, 2017).

- *Horizontal integration* uses the new technologies to exchange and manage information between customers, suppliers and business partners (S. Wang *et al.*, 2016). These closer relationships between manufacturers and broad ecosystems enable collaborative manufacturing (Dalenogare *et al.*, 2018; Santos *et al.*, 2018). The advances in collaborative networks allow companies to share company resources through industry platforms to develop products, services and other assets with more value-added, expanding the range of market opportunities (Smit *et al.*, 2016; Frank *et al.*, 2019a). For Oh and Jeong (2019), horizontal integration also increases customization. For example, supported by additive manufacturing (AM) such as 3D printing technology, new solutions in the manufacture of small batches of complex products can be offered with a high degree of customisation, increasing their perceived value and bringing greater flexibility to the production environment (Culot *et al.*, 2020a).

- *Vertical integration* refers to the integration of all hierarchical levels of the organization through advanced ICT systems, connecting production and management levels within the factory (Kagermann *et al.*, 2013). In short, the first step in ensuring vertical integration is to digitalize the shop floor using sensors, actuators and Programmable Logic Controllers (PLCs) (Godoy and Pérez, 2018). Thereafter, shop floor data is collected through Supervisory Control and Data Acquisition (SCADA) and then transferred to Manufacturing

Execution Systems (MES), which represents the managerial layer of the system and will provide the production status to the ERP. The information from production orders also flows downstream, from ERP to SCADA, which helps to deploy the resources into manufacturing orders (Tao *et al.*, 2018). The result of vertical integration is an increase in transparency and control on the shop floor, making decision-making processes more agile and reliable (Frank *et al.*, 2019a).

- *End-to-end engineering integration* takes into account all activities that aim to add value to the product from its development to after sales (Brettel *et al.*, 2014). These activities involve the expression of customer requirements, product design and development, production planning, production engineering, production, services, maintenance, and recycling. Ultimately, it facilitates mass customization as it helps to narrow the gap between different stages of manufacturing (Kagermann *et al.*, 2013).

2.7 Outcomes and Challenges

The previous sections suggest that Industry 4.0 is a very attractive and promising production paradigm. As such, it leads to many beneficial results in order to be more agile and adaptable to deal with recent trends such as growing international competition, increasing market volatility, and demand for highly individualized products (S. Wang *et al.*, 2016; Zheng *et al.*, 2018). Some relevant outcomes include:

- Mass customization: Industry 4.0 makes it possible to manufacture very low production volumes to meet individual customer needs (e.g., bach size one). Moreover, it allows customer-specific requirements to be included at any stage of product development (e.g., design, ordering, planning, and manufacture) as well as last-minute changes (Kagermann *et al.*, 2013; Zheng *et al.*, 2018).

- *Flexibility:* The self-organization and dynamic configuration enabled by CPS affects distinct aspects of business processes such as time, quality, robustness, eco-friendliness and help to cope with ever changing market requirements and discerning consumption demands (S. Wang *et al.*, 2016). As a result, engineering processes become more agile and manufacturing processes can be adjusted almost automatically to produce different types of products.

- *Optimized decision-making:* In today's landscape, it is critical to be able to make correct and agile decisions to remain competitive in the global markets. In this sense, Industry 4.0 can provide end-to-end transparency in real-time to support decision-making (Kagermann *et al.*, 2013). For example, based on big data analytics, accurate knowledge of every aspct of the factory can be provided through KPIs related to machines, products, and resource and energy consumption (S. Wang *et al.*, 2016). More accurate and agile decision-making allows production processes to be optimized across the entire value network, as well as greater resource and energy efficiency.

- *New opportunities through innovative business models:* Industry 4.0 opens up new ways of interaction in the value chain due to its high integrative and collaborative capabilities. These new forms of cooperation can represent an opportunity for companies looking to developing business to business (B2B) services as well as offering innovative services to customers (e.g., through digital platforms). It also helps companies to provide solutions for a number of issues such as meeting individual customers requirements, dynamic pricing, shortage of skilled labor, and diversity of workforce (in terms of gender, age, and cultural background) (Kagermann *et al.*, 2013).

- *Friendly to workers:* The more flexible work organization models enabled by Industry 4.0 will help workers to reach a better balance between their personal and professional development (Schwab, 2018). For example, companies can use machines to perform monotonous and repetitive tasks so that workers can perform tasks that involve more responsibility and autonomy and allow them to make full use of their skills and experience.

However, as appealing as the idea of the called "fourth industrial revolution" may sound, it is important to note that there exist some challenges, risks and barriers regarding its effective implementation (Smit *et al.*, 2016; Masood and Sonntag, 2020). The increased adoption of advanced technologies by the manufacturing industry is removing traditional industry boundaries and causing huge changes within and across organizations (Hofmann and Rüsch, 2017). These changes — which can be found in three different dimensions such as technological, social, and new business paradigms — hold many challenges and issues that must be addressed on the road to Industry 4.0.

Regarding to the *technological dimension*, there are significant challenges and risks for companies with respect to **cybersecurity** (Chang *et al.*, 2016; Smit *et al.*, 2016). With the increase in connectivity and the use of cloud-based services in Industry 4.0 environments, there is a need to protect information about customers, suppliers, know-how, systems and employees from cyber-attacks (S. Wang *et al.*, 2016). It means that security policies and new security services are necessary to keep information and processes safe and reliable, which is an essential requirement in sustaining Industry 4.0 (Lu, 2017; Oztemel and Gursev, 2020). In addition, the networked environment of Industry 4.0 requires **high speed IWN protocols (Industrial Wireless Network)** to integrate all the physical devices and information systems and form the IoT (S. Wang *et al.*, 2016). Through the IWN, smart devices can communicate with each other and self-organize, while the massive volume of data is uploaded and processed by the Cloud. However, although IWN is superior to the wired network in the manufacturing environment (e.g., industrial Ethernet), existing IWN protocols cannot provide sufficient bandwidth for heavy communication and the high volume of data transferred in Industry 4.0 systems (S. Wang *et al.*, 2016). In this sense, another critical issue is to ensure the quality and integrity of the data captured and communicated (Luthra and Kumar, 2018). The heterogeneity of manufacturing data represents a major challenge for data scientists striving to incorporate multiple data repositories with different semantics for **big data analytics** (Thoben *et al.*, 2017). The issue is to transform the huge volume of data generated into useful information that can be used for better decision-making (Oztemel and Gursev, 2020). Finally, **financial constraints** are considered to be a very important challenge for a number of new technology based initiatives in manufacturing (Luthra and Kumar, 2018). As mentioned before, especially for SMEs, challenges may arise, as they often lack financial resources and therefore cannot easily uptade and adopt advanced technologies (Mittal *et al.*, 2018a; Moeuf *et al.*, 2020).

The *social dimension* of Industry 4.0 should also be addressed. First, because Industry 4.0 changes the nature of work, since the use of new technologies requires **new ways of operation from workers** (e.g., new types of interactions between workers and machines/robots). Second, because Industry 4.0 modifies the profile of workers, once it requires new competences and skills from them (Weyer *et al.*, 2015; Piccarozzi *et al.*, 2018). The interaction between technology, jobs and skills is therefore a complex matter, that will have positive and negative impacts on workers. In fact, while new technologies can drive job creation, increase the demand for **skilled workers** and create new growth opportunities for business, they can also replace entire tasks, when they become automated or obsolete (Schwab, 2018). In addition, whether on the one hand skill gaps may lead to automation, it can represent a barrier for companies seeking to adopt new technologies (Smit *et al.*, 2016). In this regard, the literature has suggested the need of the adoption of an “augmentation strategy” (Schwab, 2018). It means that the automation of some tasks would be used to complement and empower workers, increasing their responability and autonomy and thereby enabling them to realize their unique human talents. Weyer *et al.* (2015) goes further and introduce the concept of the augmented operator. The augmented operator concept is related to the technological support given to workers in order to enable them to deal with the challenging environment of Industry 4.0 (Weyer *et al.*, 2015; Pereira and Romero, 2017). As such, technologies related to HMI such as AR can assist the cooperation between workers and robots and help with the configuration of the new manufacturing jobs (Gorecky *et al.*, 2014). Moreover, AR technologies can reflect behaviors and status of machines and products, allowing workers to monitor physical processes by visualizing meaningful data in real-time (Zheng *et al.*, 2018). As a result, workers can assume new roles in the factory (eg., flexible problem solvers and strategic decision-makers) and not only act as consumers, but also as producers of knowledge (Posada *et al.*, 2015; Weyer *et al.*, 2015; Mrugalska and Wyrwicka, 2017). Not surprisingly, the literature has acknowledged the human being as the most flexible element of the factories and, therefore, the main responsible for improving business performance (Peruzzini *et al.*, 2017; Dalenogare *et al.*, 2018; Piccarozzi *et al.*, 2018). Lastly, it has to be noted that large companies tend to have a more positive disposition towards Industry 4.0 implementation than SMEs (Smit *et al.*, 2016). In fact, it appears that many **SMEs** are not prepared for the structural changes resulting from Industry 4.0, either due to the limited technical and financial resources or because they lack awareness, which makes them more cautious in adopting a technology strategy that they are not very familiar with (Jäger *et al.*, 2016; Mittal *et al.*, 2018a). These issues will be better explored in the next section (see section 2.7).

Within the *new business paradigms dimension*, **standardization** is considered a major challenge for the large-scale implementation of Industry 4.0. It consists in the industry-wide adoption of standards, for instance through a reference architecture or system that facilitates the interoperability of the production systems of companies accross countries, enabling the complete deployment of Industry 4.0 in the global economy (Smit *et al.*, 2016). It may be applied to labelling, IT interfaces (hardware, data formats, web services), programming platforms and control software, protocols, connections, data transfer and security procedures. In other words, to ensure the interoperability of systems and the sustainability of Industry 4.0 paradigm, industries need to follow global standards and have data sharing protocols (Luthra and

Kumar, 2018). For example, in the last decade, the adoption of IoT in production systems has contributed to increase the high-volume, heterogeneity and speed of the data generated at the level of production (Khan and Turowski, 2016). Without a standardized approach to analyzing, processing and storing this information, data generated in different formats would remain incompatible worldwide and the Industry 4.0 approach would be limited to local production, restricting its ability to realize economies of scale and achieve productivity gains (Smit *et al.*, 2016). However, this will not work unless there is openness and collaboration between companies. In this context, while **collaboration** may represent a challenge for many companies, it is crucial to realize the potential of Industry 4.0 (Jäger *et al.*, 2016). Such collaboration can exist among the most varied players, for example with research institutes, universities, business partners, or direct competitors. An interesting example is when companies collaborate for the same purpose to obtain mutual benefits. For instance, through crowdsourcing practices, companies can share their manufacturing resources or services according to their demand or capacity (Kaihara *et al.*, 2017). Finally, there are also challenges for **SMEs in participating in Industry 4.0 supply chains**. As such, SMEs need to adopt the new standards and ways of working in the sector in order to increase their integration into those global digital value chains (Kagermann *et al.*, 2013). Table 2 shows a list of the main challenges faced by industries in implementing Industry 4.0.

Table 2. Main challenges in Industry 4.0 implementation

	Main challenges
Technological	• Cybersecurity: intellectual property and data privacy • High speed IWN protocols • Manufacturing big data analytics • Financial constraints (costs of development and implementation, SMEs)
Social	• New ways of working (employees' training) • Skills gap (imigration issues) • SMEs' adoption
New business paradigms	• Standardization (for large scale implemetation of Industry 4.0) • Collaboration with industry partners, customers, and direct competitors • The entry of SMEs in Industry 4.0 supply chains (costs, risks, reduced flexibility and reduced strategic independence)

It has to be noted that the opportunities and challenges presented are generalized. For example, there are much more challenges and opportunties that may arise from Industry 4.0 but that are actually related to its specific context of application. As such, despite recognizing their importance, it was decided not to extend it for two main reasons. First, because the extant literature in Industry 4.0 supports this generalization (e.g., Jäger *et al.*, 2016; Smit *et al.*, 2016; Hofmann and Rüsch, 2017). Second, because of *RQ1's* focus on SMEs. As shown in Table 2, SMEs will face challenges in all dimensions of Industry 4.0 changes. In addition, SMEs face specific challenges that differ from those of large companies (Schröder, 2016; J. Müller *et al.*, 2017; Masood and Sonntag, 2020). Therefore, to address the first goal of this thesis, the next section will be dedicated to exploring the challenges and opportunities of implementing Industry 4.0 in SMEs.

2.8 Industry 4.0 in SMEs

This section aims to answer *RQ1: What are the challenges and opportunities for SMEs in the Industry 4.0 field?* To this end, it first presents the main characteristics of an SME. It then reviews the current literature to identify research gaps that need to be addressed. Finally, it identifies common challenges and opportunities for SMEs in the fourth industrial revolution era.

2.8.1 SME's characteristics

According to the European Commission (2003), to be elegible as an SME, the following factors should be taken in consideration: *staff headcount* and either *turnover* or *balance sheet total* (see Table 3).

Table 3. SMEs' definition

Category (size)	Staff headcount	Turnover	Balace sheet total
Medium	< 250	≤ € 50 m	≤ € 43 m
Small	< 50	≤ € 10 m	≤ € 10 m
Micro	< 10	≤ € 2 m	≤ € 2 m

Source. European Commission (2003).

Given that, a SME is an enterprise that has less than 250 employees and a revenue that does not exceed €50 million or a maximum balance sheet total of €43 million (European Commission, 2003). This thesis uses this definition when referring to SMEs.

Nevertheless, the *User guide to the SME definition*, puplished by the European Commission (2020b), warns that these three factors (enterprise's size, employment, and turnover and balance sheet total) are not the only elements that must be taken into account to determine whether or not a company is an SME. In fact, there are cases that an enterprise can be small in terms of size, employees, and turnover, but it has access to additional resources either because its owned by large companies or because its linked to them. It has to be noted, however, that this upgrade of the SME's definition EC/2003 is intended to ensure that the support measures (eg., policies, grants, funding) reach only those companies that really need them, which they refer to as "genuine SMEs" (European Commission, 2020b).

In 2018, SMEs accounted for 99,8% of all enterprises in the European Union (EU-28) non-financial business sector (which includes industry, construction, trade, and services, but not enterprises in agriculture, forestry and fishery and the largely non-market service sectors such as education and health) (European Commission, 2019). They generated €4,357 billion of value added (56.4%) and employed 97.7 million people (66.6%). Among these SMEs, micro enterprises are the most common size of firms, accounting for 93% of all firms in the non-financial business sector (European Commission, 2020a). As such, SMEs are the engine of the European economy and are, therefore, essential for promoting competitiveness and employment on this continent (European Commission, 2019). The magnitude of the contribution of SMEs across the European Union demonstrates its significant importance (see Table 4).

In addition, SMEs have another set of particular characteristics that differentiate their business from other enterprises. Mittal *et al.* (2018a) discussed these characteristics grouping them into eight clusters, such as finance, technical resource availability, product specialization, standards, organizational culture, employee participation, alliances, and collaboration. Similarly, Moeuf *et al.* (2020) highlight that SMEs have specific managerial features like local management, non-functional organization, lack of expertise, short-term strategy, and lack of methods, and procedures. The authors add that these characteristics are often understood as a challenge, as they may hinder the adoption of Industry 4.0 by SMEs. Thus, they will be discussed in more detail in *section 2.8.3*.

Table 4. The number of enterprises, employment and value added by SMEs and large enterprises in the EU-28 in 2018

	Micro	Small	Medium-sized	SMEs	Large	Total
Number Enterprises	23,323,938	1,472,402	235,668	25,032,008	47,299	25,079,307
Share %	93.0%	5.9%	0.9%	99.8%	0.2%	100.0%
Number of employment	43,527,667	29,541,259	24,670,024	97,738,950	49,045,645	146,784,595
Share %	29.7%	20.1%	16.8%	66.6%	33.4%	100.0%
Value added (billion €)	1,610	1,358	1,388	4,357	3,367	7,724
Share %	20.8%	17.6%	18.0%	56.4%	43.6%	100.0%

Source. Based on the 2019 SBA Fact Sheet & Scoreboard data (European Commission, 2020a)

2.8.2 Literature findings and research gaps

The continuous development of new technologies and methods in the manufacturing sector has led to the spread of Industry 4.0 in recent years. However, the level of adoption of Industry 4.0 technologies is higher among large companies than in SMEs. In 2016, a study aimed at analyzing the Industry 4.0 initiative revealed that, although many companies recognized the need to adapt to the changes required by Industry 4.0, few of them were prepared for it, especially among SMEs (Smit *et al.*, 2016). Likewise, a survey conducted by the EU Commission indicated that more than 90% of SMEs were aware that they are lagging behind in digital innovations (Dittrich, 2016). Despite of that, much of the contemporary research on Industry 4.0 field is still disconnected from the needs of SMEs (Masood and Sonntag, 2020). A study conducted by Masood & Sonntag (2020) shows that, although this topic has been discussed for many years, it is only from 2016 that it has gained more attention.

In fact, while there are plenty of well developed studies in the literature that provide models, frameworks and toolkits for Industry 4.0 implementation, these studies are not specifically focused on SMEs (Moeuf *et al.*, 2020). As SMEs and large companies are different in terms of size, processes and the availability of resources, SMEs will require different strategies to implement Industry 4.0 (Müller *et al.*, 2017). In addition to the differences between large and small companies, each SME is also different from each other, which makes this issue more complex, since it is impossible to develop a general model that will suit all SMEs. Furthermore, SMEs usually lack experience and knowledge in regard to Industry 4.0. Thus, SMEs tend to struggle with decisions about which Industry 4.0 technologies to adopt, as well as when, where and how to integrate these technologies into their business (Mittal *et al.*, 2018a). Consequently, the introduction of Industry 4.0 technologies in SMEs is still a challenge in many aspects of manufacturing, such as production, logistics and managerial (Modrak *et al.*, 2019). Finally, as Industry 4.0 brings both challenges and opportunities, SMEs need to exploit the new possibilities of digitalization to improve their processes and develop new business models in order to compete in today's global markets. Otherwise their competitiveness could be threatened, as they would remain technogically obsolete compared to their competitors (Petrillo *et al.*, 2018). This leads to the identification of three major research gaps:

(1) most of the research in the field is still focused in large companies, neglecting that SMEs have different characteristics and priorities;
(2) there is a lack of knowledge and awareness in SMEs regarding Industry 4.0 technologies, which makes its implementation even more difficult;
(3) research on the challenges and opportunities of implementing Industry 4.0 in SMEs is still under development.

2.8.3 Challenges and opportunities for implementing Industry 4.0 in SMEs

The current literature discusses a variety of challenges, barriers, and opportunities for SMEs in implementing Industry 4.0. Jäger et al. (2016) conducted a study with around 200 companies in German and suggested major challenges and barriers on business models, high investment costs, IT security, lack of skilled workers, and legal issues. According to them, these challenges will have a strong influence on the possible adoption of Industry 4.0 by SMEs. For Schröder (2016), the biggest challenges for SMEs are the development of a comprehensive strategy, a cost–benefit analysis of the relevant technologies, data security and uniform standards, broadband infrastructure, and changes in the work environment. Müller *et al.* (2018) analyzed 68 SMEs to investigate how Industry 4.0 drive changes in their busiess models. The authors found that the high investments required to implement Industry 4.0 technologies, the lack of skilled workers, and poor managerial support are among the main barriers that impede SMEs from looking at opportunities that are outside of their core competencies (Mittal *et al.*, 2018a; Müller *et al.*, 2018). Despite this, the study suggests that SMEs can benefit from Industry 4.0, for example, through cooperation with partnering companies and institutions. Orzes *et al.*, (2019) reviewed the literature and conducted focus studies groups in USA, Italy, Austria, and Thailand to identify barriers and obstacles in Industry 4.0 implementation. The result is a list with 19 barriers/obstacles, which were categorized into six groups, such as economic-financial (high investments required, lack of monetary resources, lack of clearly defined economic benefits); cultural (lack of support by top management; preferred autonomy); competencies/resources (lack of skilled employees, lack of technical knowledge, complexity of the Industry 4.0 application both technical and practical, need to find suitable research partner), technical (lack of standards, uncertainty about the reliability of the systems, weak IT infrastructure, difficult interoperability/compatibility, technology immaturity); legal (data security concerns); and implementation process (need for new business models, lack of methodical approach for implementation, high coordination effort). Moeuf *et al.* (2020) identified risks, opportunities and critical success factors in the implementation of Industry 4.0 projects in SMEs. The study highlighted the importance of employee training, manager support, and IT infrastructure to reduce the complexity of Industry 4.0 and increase its adoption by SMEs. The study also pointed out that Industry 4.0 offers several opportunities for SMEs to improve their production process and to adopt new business models. Lastly, it suggests that Industry 4.0 is a potential driver for increasing the competitiveness of SMEs. Masood and Sonntag (2020) conducted a survey in the UK manufacturing SMEs and found out that SMEs struggle with the large number of Industry 4.0 technologies and options, the time to learn and implement them, and the funding required to implement them. Training and support from government have also been identified as relevant for the respondents in the survey. Regarding the benefits of Industry 4.0, time-to-market, reduced stockholding, and more connected supply chains were highlighted by them.

In fact, although there exist some minor differences, most research in the field highlights similar challenges and barriers faced by SMEs in adopting Industry 4.0. As such, the following 16 challenges are considered as relevant (Table 5). The intention here is not to provide an exhaustive list of challenges, but rather a comprehensive set of challenges that are commonly faced by SMEs. As these challenges are closely linked, they will be explored through their mutual interactions. In addition, as Industry 4.0 offers new opportunities for companies, specific solutions for SMEs are provided.

Table 5. Common challenges in Industry 4.0 implementation in SMEs

#	**Challenges**	**References**
1	Investment costs	(Jäger *et al.*, 2016; Müller *et al.*, 2018)
2	Lack of financial resources	(Schröder, 2016; Mittal *et al.*, 2018a; Orzes *et al.*, 2019; Moeuf *et al.*, 2020)
3	Lack of cost-benefit analysis of relevant technologies	(Jäger *et al.*, 2016; Schröder, 2016; Orzes *et al.*, 2019)
4	Adoption of advanced technologies	(Müller *et al.*, 2017; Moeuf *et al.*, 2020)
5	Lack of technical knowledge	(Mittal *et al.*, 2018a; Orzes *et al.*, 2019)
6	Skills gap	(Jäger *et al.*, 2016; Schröder, 2016)
7	Lack of top management support	(Orzes *et al.*, 2019; Moeuf *et al.*, 2020)
8	Organizational culture	(Schröder, 2016; Mittal *et al.*, 2018a)
9	Lack of collaboration strategies	(Smit *et al.*, 2016; Antoniuk *et al.*, 2017; J. Müller *et al.*, 2017; Mittal *et al.*, 2018a)
10	New business models	(Jäger *et al.*, 2016; Müller *et al.*, 2018)
11	Lack of uniform standards	(Schröder, 2016; Mittal *et al.*, 2018a; Orzes *et al.*, 2019)
12	Lack of IT infrastructure	(Kagermann *et al.*, 2013; Jäger *et al.*, 2016; Schröder, 2016; Orzes *et al.*, 2019)
13	High complexity	(Kagermann *et al.*, 2013; Schröder, 2016; Orzes *et al.*, 2019)
14	Data security issues	(Jäger *et al.*, 2016; Schröder, 2016; Orzes *et al.*, 2019)
15	Legal uncertainty	(Jäger *et al.*, 2016; Smit *et al.*, 2016; Antoniuk *et al.*, 2017)

16	Lack of comprehensive strategy of implementation	(Schröder, 2016; Orzes *et al.*, 2019)

The high **investment costs** and uncertain returns on investment caused by factors like the speed of technological improvement, the long implementation time, and the unclear market potential, have led many SMEs to approach Industry 4.0 cautiously (Jäger *et al.*, 2016). As such, SMEs tend to **avoid investing in Industry 4.0 technologies** as early adopters due to the risk of losing money by investing in the wrong technologies (Faller and Feldmüller, 2015). SMEs, therefore, need government support aimed at promoting the development of innovations in these enterprises (Jäger *et al.*, 2016; Müller *et al.*, 2018; Masood and Sonntag, 2020). The types of government support (financial and non-financial) can vary according to the policy of innovation development established in each country (Antoniuk *et al.*, 2017). In this sense, a worthwhile example is given by Irland, where the government offer grants for big IT companies on a interest-free basis for fixed investment for SMEs. France, German, Switzerland, Spain, and Portugal have also special funding programs for innovations. This support is very important, as the extant literature shows that SMEs suffer from **financial and human resource constraints** (Mittal *et al.*, 2018a; Masood and Sonntag, 2020). Since Industry 4.0 uses new technologies and requires interdisciplinary skills from workers, it is not surprising that the **lack of expertise** has also been highlighted as a risk for Industry 4.0 implementation in SMEs (Mittal *et al.*, 2018a). In this sense, appropriate employee training measures and **top management support** have been suggested to limit this risk (Masood and Sonntag, 2020; Moeuf *et al.*, 2020). SMEs are characterized by a short hierarchy, which makes the managers very close to their employees. This fact can positively affect Industry 4.0 implementation, as it facilitates communication and tranparency regarding the objectives of a given Industry 4.0 project (Moeuf *et al.*, 2020). With more trained and motivated employees, the risks of reluctance to change are reduced, making it possible the improvement of the **organizational culture** (Schröder, 2016; Orzes *et al.*, 2019).

However, on the other hand, the lack of financial resources and skilled workers in SMEs can be an opportunity for them to cooperate with other companies and institutions (Müller *et al.*, 2017). In fact, the potential of Industry 4.0 can only be realized by an **interdisciplinary collaboration** beyond company boundaries. Again, government support has a key role in understanding the financial and technological prerequisites for Industry 4.0 implementation and in providing a favorable environment (e.g., political, legislative, and economic) (Jäger *et al.*, 2016; Antoniuk *et al.*, 2017; Masood and Sonntag, 2020). For example, increasing knowledge and the exchange of experiences between SMEs, large companies, scientific institutes and universities, and creating conditions to integrate local SMEs into global knowledge networks. Particularly, great opportunities can arise through public funding programs directed at strengthening the cooperation between industry and universities/research institutions (Antoniuk *et al.*, 2017). This could expand the prospects of SMEs, as they would have access to shared knowledge and therefore would not be limited to learning from their own experience. Moreover, SMEs can take advantage of the increased connectivity enabled by Industry 4.0 to share real-time production data with their suppliers and customers in order to derive benefits for all partners within the supply chain (Khan and Turowski, 2016). For instance, customers can access real-time data to track the manufacturing stages of the ordered products (Müller *et al.*, 2018). Nevertheless, although collaboration strategies appear to be an appropriate approach for SMEs seeking to successfully implement Industry 4.0, the **lack of standards** and **data security** make it difficult for them to enter value-creating networks (Schröder, 2016; Smit *et al.*, 2016). It affects not only the interoperability of their operational systems but also the implementation of **new business models** by them (Müller *et al.*, 2018). For instance, while large enterprises adopt standards such a ISO, the presence of such standards in SMEs is scarse (Mittal *et al.*, 2018a). If large companies take advantage of their market position to set industry standards, they can force SMEs to adopt those new standards (Smit *et al.*, 2016). In Europe, many manufacturing SMEs are highly integrated in complex supply chains as they supply large and other small companies. Due to this interdenpendence, SMEs have to adopt the standards of those companies in order to remain linked to these existing suppy chains and remain competitive.

The lack of adequate **IT infrastructure** constitutes another significant challenge for SMEs (Jäger *et al.*, 2016). In recent years, IoT has received increasing attention due to its ability to integrate physical and virtual "things" into valuable information networks and connecting a factory to a variety of new smart ecosystems. Nonetheless, the development of the full potential of IoT will involve the expansion of the internet access (e.g., high speed IWN protocols) and related technologies and the security of such internet infrastructures (Schröder, 2016). A comprehensive broadband infrastructure that guarantees the security of the transferred data is a fundamental condition for the integration of IT systems, as well as for improving the efficiency and effectiveness of the supply chain over IoT. In this sense, SMEs need to expand their current broadband infrastructure and explore technologies that support high transfer rates (Schröder, 2016). In addition, data generation, storage and transfer can be a **very**

complex process that will require new ethical and legal approaches, since companies will not only be responsible for the security of their own data, but also for the data security of their supply chain partners (Müller *et al.*, 2018). Additionally, in many cases, adjustments required by law cannot be made as quickly as new technological developments can be implemented. Some aspects of these legal approaches should include the protection of corporate data (i.e., who owns the data generated and who has the right to use it), liability (i.e., who is responsible for defective products or damages), personal data (i.e., confidentiality), trade restrictions (i.e., international trade restrictions), among others (Schröder, 2016). As these **legal issues** are not yet fully defined, it remains a significant challenge for SMEs. Policymakers should, however, provide SMEs with the legal conditions to support them in their efforts to work cooperatively (Müller *et al.*, 2017). For instance, improving and developing modern laws and codes of ethics with respect to data security and ownership as well as applying punitive measures for those who violate intellectual property rights (Antoniuk *et al.*, 2017).

Finally, the **lack of a comprehensive implementation strategy** is considered a major challenge for SMEs (Smit *et al.*, 2016). Indeed, SMEs are characterized by having short-term and more cost-focused strategies, which prevents many SMEs from looking beyond their current resources and identifying the new opportunities offered by Industry 4.0 technologies. As Industry 4.0 involves a very long-term commitment, many studies have highlighted the importance of including Industry 4.0 as part of the business strategy of SMEs in order to meet their real needs (Schröder, 2016; Moeuf *et al.*, 2020). Moeuf *et al.* (2020) add that guiding SMEs to explore the data available within the company should be one of the first steps in their journey towards the adoption of Industry 4.0. According to them, the technologies that allow data exploration are already available to SMEs with affordable costs and are the most efficient to improve the performance of these type of companies. Moreover, they suggest that SMEs should consider small projects for local improvements in order to gain knowledge and experience in Industry 4.0, before to advance for a more comprehensive implementation.

2.9 Conclusions and future research directions

This chapter aimed to achieve two main aims: (1) to conduct a semi-systematic literature review to synthesize the existing Industry 4.0 literature; and (2) to identify common challenges and opportunities faced by SMEs to implement Industry 4.0. Despite the strong potential for implementing Industry 4.0 in SMEs, Industry 4.0 is relatively new to them, and needs a clearer characterization for a proper understanding and application in business. Thus, to help those manufacturing systems on their journey towards the fourth industrial revolution, 16 common challenges faced by SMEs to implement Industry 4.0 are identified. Besides, specific solutions and opportunities to overcome these challenges are provided.

Currently, to remain competitive, factors like lead time, flexibility, and the ability to produce individual and customized products efficiently and at the same cost of mass production must be improved (S. Wang *et al.*, 2016). In this sense, the literature review recognizes that Industry 4.0 introduces new types of production strategies that will directly affect competitiveness. Originated in 2011 as a future-oriented project of the German government to promote the competitiveness of its industry, Industry 4.0 also holds the status of a fourth industrial revolution. With both meanings referring to the rapid technological advancements of recent times, the general idea behind Industry 4.0 is the digitalization of the traditional industry.

From a technological point of view, CPS is the core of Industry 4.0. CPS allows production parts to communicate and cooperate with each other and with humans in real-time through information and communication technologies, such as internet of things (IoT) and human-machine interfaces (HMI). These technologies help in real-time monitoring of manufacturing processes, enabling better management of the site and use of equipment. Moreover, by connecting all entities in the value creation process, production systems become more flexible and adaptable to meet individualized customer demands. The large amount and variety of data generated by CPS, however, require additional IT technologies (i.e., IT infrastructure and analytics) that will support the organization in making informed decisions. In this context, cloud computing solutions are able to provide a customized IT infrastructure to customers at reasonable costs, while big data analytics allow to increase productivity, control costs, and ensure asset safety, leading to more efficient processes. Ultimately, the vision of a smart factory is realized through three kinds of integration: horizontal integration (i.e., value networks aimed at to integrate all stakeholders in the value chain), vertical integration (i.e., the integration of different levels of technology and information hierarchies within the smart factory), and end-to-end engineering integration (i.e., enabled by the horizontal and vertical integration). On the other hand, from a social standpoint, the results show that the human-being is the most flexible element of the factories and, therefore, fundamental in the implementation of Industry 4.0. Thereby, they should be not left behind in this new revolution.

Furthermore, the changes resulting from the implementation of advanced and disruptive technologies in manufacturing are enormous and brings benefits and challenges for companies. Some beneficial outcomes reported in the literature include: mass customization, flexibility, optimized decision-making, new business models, and a worker-friendly environment. On the other hand, among the three dimensions of change (i.e., *technological*, *social*, and *business model*), the main challenges for companies are: cybersecurity, high speed IWN protocols, manufacturing big data analytics, and financial constraints (particularly for SMEs), related to technological change; new ways of working, skills gap, and SMEs' adoption, in relation to the social change; and standardization, collaboration, and the entry of SMEs in Industry 4.0 supply chains with regard to the business paradigm change.

Finally, as can be noted, Industry 4.0 represents a challenge for businesses in general, but especially for SMEs. However, the literature review shows that the majority of research addresing Industry 4.0 is created for, or by, larger organizations, creating a lack of knowledge and awareness in SMEs regarding Industry 4.0 implementation. Given the major importance of SMEs for the european economy, the development of SMEs with regard to Industry 4.0 is critical for them to compete in the national and international contexts. In such a sense, it is important to highlight that SMEs will only reach the potential of Industry 4.0 by following implementation strategies and approaches that are specific designed for them. Otherwise they are at risk of failing before achieving the expected results.

This study is an initial effort to contribute in theory to Industry 4.0 field by identifying 16 common challenges faced by SMEs to implement Industry 4.0. Findings reveal that financial resources, investment costs, lack of cost-benefit analysis of relevant technologies, lack of technical knowledge, skills gap, adoption of advanced technologies, top management support, organizational culture, new business models, high complexity, lack of IT infrastructure, legal uncertainty, collaboration strategies, data security issues, lack of uniform standards, and lack of comprehensive strategy of implementation are among the relevant challenges faced by them. This study also contributes for practice, in particular for SME managers, providing a holistic understanding of Industry 4.0 and the potential challenges an risks in adopting it. A more clear undestanding regarding the challenges can help industrial managers to focus on the operations (e.g., design, control, optimization of the processes, etc.) that are crucial for the development of their business and eradicate potential barriers in the adoption of the modern ICT technologies. Moreover, as the study also provides specific solutions for SMEs to overcome these challenges, it can give insights for SMEs managers about the opportunities that arise with this new manufacturing paradigm.

In conclusion, this chapter presents two major limitations that can be considered opportunities for future research. First, although the methodology adopted involved the combination of qualitative and quantitative research evidence (e.g., peer reviewed literature from the largest abstract and citation database (Scopus), conference papers, government reports and consultancy reports), it used only secondary data. In this sense, the use of primary data directly collected through case studies and questionnaires with industrial managers could have contributed to increasing the reliability of the results. Thus, future research could empirically assess the results in small and medium enterprises that experience different contexts and, therefore, have distinct needs. Second, the results suggest a set of 16 common challenges faced by SMEs; future studies could extend this list to include other challenges that, for example, are related to specific conditions of certain SMEs and country contexts.

Chapter 3. Resources and Capabilities for Industry 4.0 Implementation in SMEs

This chapter presents the purpose, motivation, background, methodology, results, discussion of the results, and conclusions and future research directions.

3.1 Purpose

This chapter addresses *RQ2* and *RQ3*, i.e., *what are the resources and capabilities for Industry 4.0 implementation in SMEs?* and *how can these resources and capabilities be acquired and/or developed?* (see section 1.2). More in detail it aims to shed light on the resources and capabilities required by SMEs to successfully implement Industry 4.0 and exploit how can these resources and capabilities be acquired and/or developed. To do this, it employed an exploratory multiple case study approach and analyzed five Portuguese SMEs that have implemented Industry 4.0 technologies. Thus, it provides a comprehensive list of 33 resources/capabilities required by SMEs to successfully implement Industry 4.0. Moreover, drawn onto two major strategic management theories, i.e., resource-based view (RBV) and dynamic capability theory, it highlights how SMEs can use resources/capabilities to achieve sustainable competitive advantage.

3.2 Motivation

Industry 4.0 is one of the major trends of the industrial sector in recent years (Liao *et al*., 2017; Koh *et al*., 2019; Culot *et al*., 2020a). The term refers to the tight integration of manufacturing resources (e.g., physical objects, human actors, machinery, devices, processes and production facilities) into valuable information networks (Kagermann *et al*., 2013; Schumacher *et al*., 2016; Kolberg *et al*., 2017). This merge between the physical and digital worlds allows to gather and analyze a huge amount of data in real-time. As a result, human and machine decision-making capabilities can be enhanced based on meaningful and accurate information (Wang *et al*., 2018). Such connectivity is enabled by linking a set of advanced technologies such as information communication technology (ICT), cyber-physical systems (CPS), Internet of things (IoT), cloud computing and big data analytics (Liu and Xu, 2016). The objective is to improve the production performance in terms of productivity, quality, time, cost, and flexibility (Frank *et al*., 2019; Mittal *et al*., 2019).

Although the topic has been heavily discussed among researchers, practitioners and policymakers (Bitkom *et al.*, 2016; Liao *et al.*, 2017; Schwab, 2018), research on Industry 4.0 implementation is still under investigation (Lee *et al.*, 2015; Frank *et al.*, 2019; Moeuf *et al.*, 2020). In particular, the resources/capabilities required to implement Industry 4.0 have not been fully exploited in current literature. In addition, previous studies (i.e., Neirotti *et al.*, 2017; Hasselblatt *et al.*, 2018; Mittal *et al.*, 2018a; Moeuf *et al.*, 2018; Frank *et al.*, 2019; Moeuf *et al.*, 2020) are characterized by the following significant limitations. First, they consider only a narrow set of resources/capabilities for Industry 4.0 implementation (Neirotti *et al.*, 2017; Hasselblatt *et al.*, 2018; Moeuf *et al.*, 2018; Frank *et al.*, 2019). Second, they are usually focused on large enterprises (Hasselblatt et al., 2018; Frank *et al.*, 2019). Despite that fact that small and medium enterprises (SMEs) play a significant role in economic development of most countries (Li et al., 2016), they are mostly neglected by Industry 4.0 literature. Third, it is still unclear in the extant literature how can SMEs acquire/develop these resources/capabilities (Neirotti et al., 2017). Finally, previous studies are rarely grounded in mainstream theories, such as resource-based view (RBV) and dynamic capability theory *(Neirotti et al.*, 2017; Hasselblatt *et al.*, 2018).

This chapter seeks to fill the abovementioned gaps by answering to the following two research questions: (1) *What are the resources and capabilities for Industry 4.0 implementation in SMEs?* (2) *How can these resources and capabilities be acquired and/or developed?* To do this, a multiple case study analysis in five Portuguese SMEs from three different sectors (automotive, automation and textile) was conducted. Such a method is strongly recommended to answer *why* and *how* questions, since it allows a good understanding of the complete phenomenon. Moreover, drawn on two major strategic management theories, i.e., resource-based view (RBV) and dynamic capability theory, this chapter seeks empirical evidence on how SMEs can use resources and capabilities to achieve sustainable competitive advantage. Following Barney *et al.* (2012), this study argues that competitive advantage is the first step to advance the firm's path towards success. Finally, as the literature shows that empirical evidence and analysis are still limited, additional evidence can be useful to support companies in predicting investment implications (Cimini *et al.*, 2020).

The results show that the Portuguese SMEs do not require all available Industry 4.0 resources and capabilities. They adopt indeed Industry 4.0 step by step and tend to prioritize the resources and capabilities that enable real-time data collection and increase connectivity. For these SMEs, the exploitation of data in real-time is a mean to react more efficiently to market changes and, therefore, gain competitive advantage.

Moreover, the study found that the Portuguese SMEs use two different ways to acquire and/or develop resources and capabilities; internally (e.g., R&D oriented to new digital technologies, advanced human resources practices and top management commitment); and externally (e.g., hiring skilled employees and through innovative collaboration networks).

In sum, this chapter aims to advance the general debate on Industry 4.0 implementation. More in detail, it is among the first studies to carry out an analysis of the resources and capabilities for Industry 4.0 implementation in SMEs through the lens of RBV and dynamic capability theory. In doing so, it aims to provide insights to SMEs, to help them to recognize and scale the resources and capabilities needed to successfully embrace all the benefits of Industry 4.0.

3.3 Background

This section presents the theoretical background of chapter 3: the RBV and dynamic capabilities theory (Section 3.3.1) and the literature on resources/capabilities for Industry 4.0 implementation in SMEs (Section 3.3.2). The choice of using those theories was made due to two main reasons. First, The RBV theory was used to highlight how firm's unique and strategic resources/capabilities can determine competitive outcomes. Second, as RBV theory does not consider changes in context, dynamic capabilities are vital for understanding how companies respond to waves of change (Teece, 2023).

3.3.1 Resource-based view and dynamic capability

The *resource-based view (RBV)* emphasizes the importance of the firm's resources as a potential source to gain and sustain competitive advantage (Barney, 1991). According to RBV, resources are the tangible and intangible assets (e.g., financial, physical, human, technological, reputational, organizational, and so forth), that firms use to conceive of and implement value creation strategies (Wernerfelt, 1984; Barney, 1986, 1991).

So far, strategic management researchers have proposed distinct taxonomies aimed at providing more detailed descriptions and exploring which types of resources allow firms to gain competitive advantage and sustain it over a longer period. As such, RBV theorists suggest that only strategic and useful resources can provide sustained competitive advantages and be a source of economic profits because of their properties of value, rareness, inimitability, and non-substitutability (Barney, 1991, 2001). In this sense, Prahalad and Hamel (1990) draw attention on a critical category of resources, called firm's capabilities. Makadok (2001) defines capabilities as "a special type of resource, specifically an organisationally embedded non-transferable firm-specific resource whose purpose is to improve the productivity of the other resources possessed by the firm". In this definition, Makadok (2001) highlights two key features that differentiate capabilities from other firm's resources. First, capabilities cannot be easily transferred, bought and sold, since they are firm-specific resources, developed over time and embedded in the organization processes (Teece *et al.*, 1997). Second, the main purpose of capabilities is to enhance the productivity of the other resources possessed by the firm (Schoemaker and Amit, 1993). According to Helfat and Winter (2011), the capabilities to deploy resources are the basis for establishing competitive advantage.

Nevertheless, although RBV focus on existing firm's resources and capabilities as drivers for achieving sustained competitive advantage, scholars also emphasise that their further development must be considered equal or even more important than possession and utilization (Leonard-Barton, 1992; Teece *et al.*, 1997; Lasi *et al.*, 2014). In this sense, they argue that the dynamic capability theory is more suitable to address firm's performance (see e.g., Leonard-Barton, 1992; Teece *et al.*, 1997).

With its roots in RBV, the *dynamic capability theory* attempts to understand the mechanisms (e.g., skill acquisition, capability building and procedures), that firms use to build, integrate and reconfigure internal and external resources and competences to address rapidly changing environments (Teece *et al.*, 1997; Irfan *et al.*, 2019). In general, the dynamic capabilities are based on managerial and entrepreneurial resources and capabilities, such as Research and Development (R&D), top management commitment, training and so on, that are aimed at matching internal competences with the requirements of a certain business environmental (Teece *et al.*, 1997; Brenner, 2018). The concept is basically focused on the ability of firms to learn and evolve (Teece *et al.*, 1997). Although few differences exist between the resources, competencies, and capabilities concepts, RBV and dynamic capability theorists argue that they are all a potential source of sustainable competitive advantage for companies (Barney, 1986, 1991; Teece *et al.*, 1997). They will therefore be analyzed together in this chapter (a similar approach was followed by Harland and Knight, 2001, among others).

3.3.2 Resources and Capabilities for Industry 4.0 implementation in SMEs

Industry 4.0 is attracting increasing attention in the scientific literature (Frank *et al.*, 2019; Moeuf *et al.*, 2020; Culot *et al.*, 2020a). Research has focused so far on different topics, such as development of specific technological Industry 4.0 solutions (Helo *et al.*, 2014; Ren *et al.*, 2015; Cheng *et al.*, 2018); business models (Müller *et al.*, 2018; Safar *et al.*, 2018); Industry 4.0 maturity and readiness models (Ganzarain and Errasti, 2016; Mittal *et al.*, 2018b); interaction of Industry 4.0 with other management paradigm like Lean Manufacturing (Kolberg and Zühlke, 2015; Tortorella and Fettermann, 2017; Buer *et al.*, 2018; Pagliosa and Tortorella, 2019); the effects of Industry 4.0 on performance (Dalenogare et al., 2018; Kamble, Gunasekaran and Dhone 2019) and Industry 4.0 implementation (Frank *et al.*, 2019; Mittal *et al.*, 2019; Moeuf *et al.*, 2020; Cimini *et al.*, 2020). For a systematic review on Industry 4.0, see Liao *et al.* (2017), Piccarozzi *et al.* (2018); Oztemel and Gursev (2020), Bai *et al.* (2020) among others.

Some studies have also started to shed light on the resources and capabilities required by SMEs to successfully implement Industry 4.0 (Mittal *et al.*, 2018a, 2019; Moeuf *et al.*, 2020). For instance, Neirotti *et al.*, (2017) investigated how SMEs develop ICT organizational capabilities in response to the external environment conditions. Hasselblatt *et al.* (2018) identified the capabilities required to build, sell and deliver IoT solutions. Moeuf et al. (2018) analyzed the technical resources and the managerial capabilities needed by SMEs to achieve their target performance objectives on the Industry 4.0 context. Mittal *et al.* (2018a) reviewed the existing Industry 4.0 maturity models and provided suggestions for adapting these models to support SMEs moving towards Industry 4.0. In doing so, they identified what are the SMEs requirements to implement Industry 4.0. Mittal *et al.* (2019) presented a SME adoption framework based on real cases and built on the needs and challenges faced by SMEs. Garbellano and Da Veiga (2019) highlighted how Industry 4.0 technology transfer has been implemented by Italian SMEs and emphasize the ‘orchestration’ role of the management team. Moeuf *et al.* (2020) conducted a Delphi study supplemented by Régnier’s abacus by consulting 12 selected experts to identify the risks, opportunities and critical success factors to implement Industry 4.0 in SMEs.

The aforementioned studies are however characterized by at least two major limitations. First, there is a lack of evidence about how can SMEs acquire and/or develop resources and capabilities to implement Industry 4.0 (Neirotti *et al.*, 2017). Second, despite the importance of considering grand theories in management research (e.g., Brenner, 2018), these studies – with few exceptions (e.g., Garbellano and Da Veiga, 2019; Wamba *et al.*, 2017) – are not adequately grounded on mainstream theories such as RBV and dynamic capabilities (Neirotti *et al.*, 2017; Hasselblatt *et al.*, 2018). Indeed, as Industry 4.0 relies on many elements that SMEs often struggle to perform, as they are less capable of coping with the financial, technological and staffing challenges than large companies (Sommer, 2015; Moeuf *et al.*, 2020), they need to be very efficient in allocating their capital in order to get the best results while minimising the use of resources (Faller and Feldmüller, 2015). As such, it seems important to investigate how SMEs can use resources and capabilities to gain and sustain their competitive advantage.

To address these gaps, this study first summarized the literature to develop a comprehensive list of the resources and capabilities that SMEs might need to successfully implement Industry 4.0. In order to avoid redundancy, since the literature may use different names for the same type of technologies or concepts, this list was refined considering the basic characteristics and objectives of each resource and capability, which resulted in a list with 33 resources and capabilities (see Table 6). In addition, to provide a more comprehensive picture of these Industry 4.0 resources and capabilities, we categorize them into three dimensions, i.e., *technological*, *organizational* and *external*. This categorization takes into account distinct levels of the manufacturing processes such as shop-floor, organizational/management and cross-organizational, in order to cover the basic principles of Industry 4.0, i.e., vertical integration, horizontal integration and end-to-end engineering (S. Wang *et al.*, 2016).

In this sense, the technological dimension includes the primary technological resources, such as physical/digital interfaces, network technologies, data processing and digital/physical process technologies (see Culot *et al.*, 2020a). The organizational dimension involves management practices, processes and learning. Here, consistently with the dynamic capability theory, new capabilities can be built and developed over time. Lastly, the external dimension encompasses financial support, policies, suppliers, customers and markets. In this dimension, resources and capabilities such as business model, funding, standards and innovative collaboration networks are considered.

Table 6. Resources and capabilities for Industry 4.0 implementation in SMEs

		Resources/Capabilities	Exemplary references
Technological	1	Additive manufacturing/3D printing	Singh *et al.* (2019)
	2	Advanced/Collaborative Robotics/ Autonomous vehicles	Moeuf *et al.* (2018); Singh *et al.* (2019)
	3	Artificial Intelligence	Tao *et al.* (2018); Singh *et al.* (2019)
	4	Big Data and Data Analytics	Wamba *et al.* (2017); Moeuf *et al.* (2018); Singh *et al.* (2019); *Moeuf et al.* (2020)
	5	Cloud Computing/ High-performance computing	Helo (2014); Singh *et al.* (2019)
	6	Customer Relationship Management (CRM)	Masood and Sonntag (2020)
	7	Cyber-Physical System (CPS)	Moeuf *et al.* (2018); Singh *et al.* (2019)
	8	Cybersecurity	Moeuf *et al.* (2018); Moeuf *et al.* (2020)
	9	Enterprise Resource Planning (ERP)	Helo (2014); Müller *et al.* (2017); Masood and Sonntag (2020)
	10	Human Machine Interfaces (HMI)/Wearables/Mobile devices (tablets, smartphones, etc.)	Modrak *et al.* (2019); Müller *et al.* (2017); Schwab (2018)
	11	Internet of Things (IoT)	Moeuf *et al.*(2018); Singh *et al.* (2019); Moeuf *et al.* (2020)
	12	Machine to Machine Communication (M2M)	Gilchrist (2016); Modrak *et al.* (2019); Moeuf *et al.* (2018)
	13	Manufacturing Execution System (MES)	Helo (2014)
	14	Product Lifecycle Management (PLM)	Safar *et al.* (2018)
	15	Supplier Relationship Management (SRM)	Müller *et al.* (2020)
	16	RFID/QR Code/Barcode	Modrak *et al.* (2019); Moeuf *et al.* (2018)
	17	Sensors and Actuators	Ricci *et al.* (2021)
	18	Simulation software	Moeuf *et al.* (2018); Moeuf *et al.* (2020)
	19	Virtual Reality (VR)/Augmented Reality (AR)	Rauch *et al.* (2019)
	20	Internet technologies (web services, wireless, broad-band networks)	Kumar *et al.* (2020)
Organizational	21	Advanced human resource management practices (including training)	Moeuf *et al.* (2020); Schwab (2018)
	22	Alignment between departments and IT	Mittal *et al.* (2018a)
	23	Digital Culture	European Commission (2017)
	24	Digital skills	Agostini and Filippini (2019)
	25	R&D oriented to new digital technologies	Kumar *et al.* (2020); Mittal *et al.* (2018a)
	26	IT structure	Moeuf *et al.* (2020)
	27	Innovation	Schwab (2018)
	28	Knowledge decision-making techniques (agility)	Rauch *et al.* (2019)
	29	Top management commitment	Moeuf *et al.* (2020); Schwab (2018)
External	30	Business model	Culot *et al.* (2020); Moeuf *et al.* (2020)
	31	Financial incentives (public and private funding)	Masood and Sonntag (2020); Mittal *et al.* (2018a)
	32	Industrial polices and standards consideration	Mittal *et al.* (2018a)
	33	Innovative collaboration networks (with research institutes, vendors, and suppliers)	Mittal *et al.* (2018a); Moeuf *et al.* (2020)

3.4 Methodology

This section presents the methodology used in this chapter. Thus, it describes the research method, sample selection, data collection, coding and data analysis and, finally, validy and realibility.

3.4.1 Research Method

This chapter uses an exploratory research design through a multiple case study analysis to identify the resources and capabilities required by SMEs to implement Industry 4.0. The case study method is a very appropriate approach to interact with organizations since it is an observation-based method that facilitates the development of in-depth investigations in different contexts of reality while providing immediate validation of the findings. In the end, evidence of each case company can be compared by developing a cross-case analysis (Dieste *et al.*, 2020; Eisenhardt, 1989). In addition, within dynamic fields such as operations management, case study research method has been considered a powerful means to cope with the growing changes in technology and management practices (Lewis, 1998; Voss *et al.*, 2002; Yin, 2009). Some noteworthy examples are the studies on the role of the manufacturing technology in business strategy by Meredith and Vineyard (1993) and on the flexibility of industrial additive manufacturing systems developed by Eyers *et al.* (2018).

Nevertheless, although case research may have some disadvantages, as it often requires considerable resources and time, and caution is required in generalizing the conclusions of a limited set of cases, it also provides several advantages. For instance, through triangulation of multiple sources of data, case studies allow a richer understanding of a real-life context, and then relevant insights and theory may emerge from the study of a particular phenomenon (Voss *et al.*, 2002; Yin, 2009).

3.4.2 Sample Selection

One of the reasons that motivated this study comes from the current status of the Portuguese SMEs. As it is well-known, SMEs are considered the backbone of most economies, including Portugal, where they represent approximately 99.9% of the country's companies (European Commission, 2019). Moreover, in the last few years, the Portuguese SMEs have shown a consistent growth, with its value-added increasing by more than 5% over year between 2013-2017. In fact, surprisingly, between 2016-2017, the Portuguese SMEs grew more quickly than large companies (European Commission, 2019). Based on this, the Digital Economy & Society Index, performed by European Commission, stated that Portugal has the infrastructures and innovation capabilities needed to drive the digital transformation of its industry (European Commission, 2017). In this regard, the Portuguese National Strategy for the Digitization of the Economy (Industry 4.0) is promoting digitization focused on identifying the real needs of the Portuguese industry, particularly of SMEs. The overall objective is to increase competitiveness and then strengthen Portugal's role in the fourth Industrial Revolution (European Commission, 2019).

Hence, in this study the unit of analysis is the SME. It was adopted a theoretical sampling method (Eisenhardt, 1989; Patton, 2002) and selected heterogeneous cases in terms of industries (e.g., plastic compounds, mechatronics solutions, accessories and metal components, equipment and automation systems, and textiles products), and homogeneous cases in terms of country (Portugal) (a similar approach was adopted by Ciano *et al.*, 2020, among others). This country specific approach allows for controlling for several critical factors relating to the diversity of national contexts (Secchi and Camuffo, 2016). The selected SMEs represent well-established and successful businesses in Portugal and their characteristics were particularly suitable to examine the resources and capabilities needed to implement Industry 4.0 in SMEs. In total, 6 cases were chosen for the study. However, even by using secondary data and personal contacts, it was not easy to identify a-priori the level of Industry 4.0 knowledge and implementation of the companies. For this reason, one case was excluded since the level of implementation of Industry 4.0 was too low for obtaining significant findings for the study. Hence, the final sample consists of five SMEs with a good or very good experience on Industry 4.0 implementation. In the literature there is a general consensus regarding the sample size, which suggests that 4-10 case studies can generate credible explanations, as well as the generalization of the results (Curtis *et al.* 2000; Jaca *et al.* 2014). Eisenhardt (1989) and Barratt *et al.* (2011) advise that if less than 4 cases are used, it may be more challenging to capture the complexity of reality. On the other hand, if more than 10 case studies are employed it could become problematic for scholars to analyse data. Previous studies in the operations management research field such as Mirzaei *et al.* (2021), Dieste *et al.* (2020) and Iakymenko *et al.* (2020) deployed a multiple case study approach using five case companies.

Table 7 shows the main characteristics of the sample (it uses code names to preserve the anonymity of the companies).

Table 7. Company and interviewee profile

Company	**Sector**	**Employees**	**Turnover**	**Products and services**	**Interviewee position**	**Interviewee seniority**
A	Automotive	80	25,0M€	Development of plastic compounds	Production Maintenance and Logistics manager	8 years
B	Automotive	46	10,0M€	Solutions in mechatronics	R&D and Production manager	8 years
C	Automotive	240	45,0M€	Manufacture of accessories and metal components	Continuous improvement and Human Resources manager	22 years
D	Automation	57	12,5M€	Commercialization and development of equipment and automation systems	Marketing manager	8 years
E	Textile	180	15,0M€	Manufacture of textiles and wool products	Maintenance and IT manager	12 years

3.4.3 Data Collection

The data collection process was based on in-depth semi-structured interviews using pre-determined topics, and open-ended questions. Data from company's reports, websites, observations, and field notes were also collected. This enabled the abovementioned triangulation between methods and provided increased reliability of data (Barratt *et al.*, 2011). The interview protocol was defined based on the review of the relevant literature (see Chapter 2). Then it was sent to other researchers in the field in order to verify if the questions were well formulated. After that, the interview protocol was ajusted. It was opted to conduct semi-structured interviews in order to keep the interview structure open and, thus, allow the interviewees to freely share their experience on the subject (Tzeng *et al.*, 2008).

The interview protocol (see Appendix I) consisted of two parts: (A) company profile and (B) Industry 4.0. The Industry 4.0 section was subdivided into two further sub-sections, namely: envision of Industry 4.0 and resources and capabilities for Industry 4.0 implementation. In the Industry 4.0 implementation section, first, respondents were provided with a list of the 33 resources and capabilities identified in the literature review, they were asked to identify the useful/necessary resources and capabilities to implement Industry 4.0 and whether they would like to add any other resources or capabilities that was not listed. Second, they were asked if they already had it when they started their first Industry 4.0 projects. Finally, they were asked how these resources and capabilities are acquired and/or developed by the company and how can other stakeholders (e.g., government, schools/universities, suppliers/customers) support them in the implementation of Industry 4.0. During the entire process, further follow-up questions were made by phone or were sent by e-mail to complete the data collection process.

The interviews were performed between October 2018 and January 2019 with managers from different departments and areas, including product and processes development, production, logistics, maintenance, equipment development and IT, continuous improvement, and marketing. Moreover, the selected interviewees were responsible for the implementation of the Industry 4.0 projects in their respective companies. Since SMEs have a short hierarchical line (Moeuf *et al.*, 2020), the interviewed managers had enough knowledge and experience to provide us the information needed for our study. The interviews were conducted in person (or via Skype) and lasted approximately 1-2 hours. When considered necessary the interviewee was interviewed twice or more. The interviews were conducted in Portuguese (see Appendix II) and afterwards transcribed and translated to English (see Appendix III).

3.4.4 Coding and data Analysis

Coding and data analysis were conducted manually by two authors, to ensure inter-coder reliability (Duriau *et al.*, 2007). The few disagreements in the coding were discussed and resolved, also with the help of the third author, who was assigned the role of “resident devil’s advocate”.

According to Eisenhardt (1989) two data analysis steps should be followed: within case analysis and then searching for cross-case patterns. Therefore, first, the five cases were considered to be independent, and then, similarities and divergences between the cases were sought. However, due to space limitations, it was decided to report in the study only the cross-case analysis.

3.4.5 Validity and reliability

It was used multiple sources of evidence during the data collection processes (e.g., interview protocol, company’s reports, websites, field notes and observations), seeking triangulation and then strengthening construct validity (Eisenhardt, 1989; Voss *et al.*, 2002).

To enhance external validity, this study adopted a heterogeneous sample of the unit of analysis (five companies from three different sectors) (Ciano *et al.*, 2020).

Finally, to achieve reliability it was created a data base for each case study which is composed by the interview transcripts, archival data from company's reports and websites, field notes and the data from the cross-case analysis (Eisenhardt, 1989; Voss *et al.*, 2002). In this study, in addition to taking notes during the interviews, they were also recorded for documentation purposes.

3.5 Results

The cross-case analysis allowed to identify the key resources and capabilities for Industry 4.0 implementation in SMEs (see section 3.5.1) and to shed light on how the SMEs acquire and/or develop these resources and capabilities (see section 3.5.2). To provide a chain of evidence some excerpts from the interviews were reported.

3.5.1 Resources and capabilities for Industry 4.0 implementation in SMEs

As far as Industry 4.0 implementation is concerned, all respondents agreed that the availability of adequate technology to gather real-time data is a valuable resource as it improves the decision-making processes. According to the interviewees, consistent data is an important condition to value creation, especially when companies operate under changing environments. For implementing Industry 4.0, the sampled SMEs identify therefore the need to adopt technologies such as sensors, *RFID*, *QR Code* and *Barcode*. These technologies are in fact used to monitor and control equipment, product, shop floor processes, as well in logistics. For instance, company B says: "*After the implementation of our first Industry 4.0 project (employment of sensors and RFID technologies), through a smartphone app we are informed almost instantaneously that the machine 'A' failed this morning and this will result in a downtime at 4pm on the x-line equipment. This allows us to make better decisions to react to these unpredictable events*". Company A reported that one of their Industry 4.0 projects concerns the monitoring of the equipment condition and the energy consumption of the processes. By using sensors and wireless internet it is possible to control the condition of the machines in terms of vibration, temperature, efficiency or controlling the energy consumption by machine or upon the general system. As an energy intensive consumer, these data are extremely valuable for the company. Only company E reveals difficulties in implementing this type of technology in its products. The company, which belongs to the textile sector, describe that when a piece comes out of the loom, it must have a serial number written on it. The problem is that when the fabric advances on the production processes, the following treatments can be violent and destructive for

RFID tags or *QR codes*, which narrows the adoption of these technologies by the company.

The (management) information systems, such as *Enterprise Resource Planning (ERP)* and *Manufacturing Execution System (MES)*, are other technologies identified by all SMEs as important resources for implementing Industry 4.0, as they allow storage and sharing of information and, consequently, improve visibility. Nonetheless, due to the delays in the communication between *ERP* and *MES* and the lack of flexibility in these systems to support distributed manufacturing, new technologies could be introduced. For the interviewed companies, *cloud computing* can handle the weakness of current *ERP/MES* systems. For instance, company A, which shares a cloud computing system with its plant in Mexico, says: "*Cloud computing allows us to monitor and to control our plant in Mexico through horizontal integration, as well as providing faster feedback if any problem arise*". A possible reason for the high adoption of cloud-based solutions in SMEs might be that despite this technology is less revolutionary than others (e.g., CPS, IoT, machine to machine communication, advanced robots), it requires almost no investment in in-house resources and can be easily customized according to the needs of the company (Moeuf *et al.*, 2018). Only in one case (company E), the respondent reveals some mistrust on the cloud-based solutions. In this regard, company E says: "*We bought an external cloud server two years ago. However, we are still not convinced if it was a good idea, not because of security, or because we are at risk by having a server inside or outside the factory, but because we no longer have control of our data. So, if any problem occurs, we depend on third parties*". In fact, regarding the implementation of specific cybersecurity technologies, most respondents mention that there are no major concerns as they believe that cloud computing already provide this service.

According to the respondents, the improvements in the computational potential of recent years, in terms of clusters and cloud, have leveraged the importance of *simulation software* to implement Industry 4.0, as it allows better analyses and feedback to support the decision-making process (Xu *et al.*, 2016). Nonetheless, within the sample, only two companies (companies B and E) report that they use simulation models to optimize their resources and processes. For instance, company E mention: "*We already have a software that optimize and plan the processes for each machine*". The same companies also reported to have taken advantage of emerging technologies such as *human machine interfaces (HMI)/wearables* to support their employees. According to them, these technologies make employees more engaged since they facilitate automated information exchange and tracking. Enabling them to fully use their skills and experience.

All sampled SMEs highlight *internet technologies* - service-oriented architecture, web services, Web 2.0, wireless, broad-band networks (Helo *et al.*, 2014) - as critical resources towards Industry 4.0 implementation. However, although all the companies already use *wireless technologies* in their plants, only two companies (companies B e D) reported having adopted a technology able to offer advanced connectivity, such as *internet of things (IoT).*

In sum, technologies enabling real-time information sharing are of capital importance for the SMEs surveyed as they provide flexibility and opportunities for monitor processes. Furthermore, Industry 4.0 technologies have been recognised by company managers as a great opportunity for quality improvement and, in the end, for value creation.

As far as the organizational resources and capabilities are concerned, the sampled SMEs referred to the importance of a strong *top management commitment* to carry out Industry 4.0 projects. The five SMEs reported having a great experience in applying Lean Manufacturing practices such as visual management and kaizen, which helps them in communication and transparency concerning the Industry 4.0 objectives. They argue that when the communication between employees and managers is open and direct, employees are more willing to accept changes. In this regard, companies A, B, D, and E highlighted the development of a *digital culture* at both levels, individual and organizational, as an imperative capability for companies wishing to implement Industry 4.0.

Companies A, B, D, and E mentioned *R&D oriented to new digital technologies* as an important resource to leverage company's *innovation capabilities*, and hence for Industry 4.0 implementation. Company A says: "*Now we are working on products to be released in the next 4 or 5 years, that is, we are anticipating the market requirements, otherwise we will die quickly*". These four SMEs have a R&D department that is linked to other departments (e.g., quality, production) and it is aligned with the new digital trends. In this sense, all interviewees consider the importance of the *alignment between departments and IT*. The SMEs also underline that the company's *IT structure* is a key resource to support the flow of information. They argue that faster and more accurate flow of information leads to improved decision-making processes. Despite this, only company B reported exploring *Knowledge decision-making techniques*.

Furthermore, as Industry 4.0 paradigm changes the roles within industries, the skills required to perform most jobs have already changed significantly. As such, the sampled SMEs pointed to *digital skills* (e.g., personal, technical and managerial) as a critical capability to implement Industry 4.0. Nonetheless, all respondents report that they face an increasing difficulty to hire digital skilled employees who can deal with the complexity and the dynamics posed by Industry 4.0. This shortage of talents force companies to adopt *advanced human resource management practices (including training)*, in order to support their employees through reskilling and upskilling. For instance, company B highlights the central role of employees in the Industry 4.0 environment: *"We must take advantage of their potential in developing ideas and solutions"*. *Company B adds: "We perform an annual assessment at the company in order to identify our training needs"*. In this regard, most companies report partnerships agreements with external consultants, training organizations, and governments.

In conclusion, the Portuguese SMEs investigated highlight the importance of a skilled and committed staff, from shop-floor employees to managers. In this sense, most companies recognize Lean Manufacturing practices as an important enabler for the implementation of Industry 4.0 solutions (Zangiacomi *et al*., 2020). Moreover, firms recognise the importance of developing horizontal, and vertical connection of people, machines, objects to create a dynamic IT structure for managing complex systems (Kiel *et al*., 2017).

As far as the external resources and capabilities are concerned, the SMEs reported establishing *innovative collaboration networks* (e.g., collaboration with universities and research institutes, Government institutes and customers and suppliers). For example, several companies referred that offering customized products and solutions to customers is a capability with increasing relevance in Industry 4.0 contexts. According to them, companies that take into account all relevant stages of value creation from the customer perspective (e.g., improving customer experience from order to delivery) will be able to create competitive advantage. In this regard, company B says: *"As a SME, we differentiate ourselves from large companies by having the ability to customize and adapt our products to the customer's needs"*. *Company B adds: "We have this flexibility that the multinationals do not have"*. *Company E mentions: "Because many of the industry needs arise from very specific* *processes, we use our know-how to provide them customized solutions*". These types of innovative collaboration networks are considered by the sampled SMEs as critical capabilities to face the challenges in implementing Industry 4.0 and, subsequently, to create and sustain competitive advantage.

As it might be expected all interviewed SMEs consider external resources such as *financial incentives and industrial policies and standards* as critical resources to support Industry 4.0 implementation. Some interviewees mention that they are receiving government support through Portugal 2020 funds for the adoption of technologies and infrastructures under the Industry 4.0 concept. However, all interviewees highlight that, despite having the necessary resources and capabilities, many other SMEs in Portugal are facing difficulties to get them. They believe that this is one of the reasons why these companies are not investing on the emerging technologies in some industrial processes, which places Portugal a little behind other countries in the digital transformation.

Regarding *industrial policies and standards*, interviewees highlight the need of more government policies and secure international standards. For example, company B emphasizes the importance of creating educational policies that promote the use of new technologies on workers of all ages. Company A underlines the increasing importance of sustainability issues since "*Today, taking sustainability issues into account is very important from the market point of view*". Moreover, most companies mentioned the importance of secure standards to getting partners and join value creation networks.

The aforementioned resources and capabilities were considered relevant for the SMEs to adopt and implement Industry 4.0. As such, they were used as an empirical evidence to support the set of resources and capabilities identified in the literature review section.

Table 8 indicates that *additive manufacturing*/3D printing, *CPS*, *M2M*, *SRM*, *VR/AR* technological resources were not listed by any of the companies analyzed. Besides, none of the SMEs remarked the use of *new business models* from the external resources and capabilities category.

Table 8. Resources and capabilities for Industry 4.0 implementation in Portuguese SMEs

	#	**Resources/Capabilities**	**A**	**B**	**C**	**D**	**E**
	1	Additive manufacturing/3D printing					
Technological	2	Advanced/Collaborative Robotics		x			
	3	Artificial Intelligence				x	
	4	Big Data and Data Analytics				x	x
	5	Cloud Computing/ High-performance computing	x	x	x	x	x
	6	Customer Relationship Management (CRM)		x			
	7	Cyber-Physical System (CPS)					
	8	Cybersecurity	x	x	x	x	x
	9	Enterprise Resource Planning (ERP)	x	x	x	x	x
	10	Human Machine Interfaces (HMI) - Mobile devices (tablets, smartphones, etc.)/wearables		x			x
	11	Internet of Things (IoT)		x		x	
	12	Machine to Machine Communication (M2M)					
	13	Manufacturing Execution System (MES)	x	x	x	x	x
	14	Product Lifecycle Management (PLM)		x			
	15	Supplier Relationship Management (SRM)					
	16	RFID/QR Code/Barcode	x	x	x	x	
	17	Sensors and Actuators	x	x	x	x	
	18	Simulation software		x			x
	19	Virtual Reality (VR)/Augmented Reality (AR)					
	20	Internet technologies (web services, wireless, broad-band networks)	x	x	x	x	x
Organizational	21	Advanced human resource management practices (including training)	x	x		x	
	22	Alignment between departments and IT	x	x	x	x	x
	23	Digital Culture	x	x		x	x
	24	Digital skills	x	x	x	x	x
	25	R&D oriented to new digital technologies	x	x		x	x
	26	IT structure	x	x	x	x	x
	27	Innovation	x	x		x	x
	28	Knowledge decision-making techniques (agility)		x			
	29	Top management commitment	x	x	x	x	x
External	30	Business model					
	31	Financial incentives (public and private funding)	x	x	x	x	x
	32	Industrial polices and standards consideration	x	x	x	x	x
	33	Innovative collaboration networks (with research institutes, vendors and suppliers)	x	x	x	x	x

3.5.2 Industry 4.0 resources and capabilities development

The results show that the resources and capabilities required for Industry 4.0 implementation in SMEs can be acquired and/or developed both *internally* and *externally*.

As for *internally*, the SMEs suggest three different ways whereby they can acquire and/or develop the necessary resources and capabilities. For instance, companies A, B, D, and E mention *R&D oriented to new digital technologies* as a valuable way to internally develop new products and innovation capabilities. For these SMEs, performing internal research is imperative to predict market needs and strengthen competitiveness. *Top management commitment* was also reported by most of the SMEs as a critical capability to develop resources and capabilities for Industry 4.0 implementation. According to them, the manager plays an important role in the development of the digital culture among employees by facilitating the smooth adoption of the necessary changes. All SMEs stated that when employees understand the dominant values of the company and they are aware of the role of new technologies in their day-to-day work, they are more likely to bridge the gap between the company and the requirements of the external environment. Finally, the interviewed SMEs reported using *advanced human management practices* oriented to improve digital skills. As Industry 4.0 requires a reallocation of tasks, new responsibilities and skills for employees, all SMEs recognize the importance of offering training to help their employees deal with Industry 4.0.

Nonetheless, the Portuguese SMEs also acquire and/or develop the necessary resources and capabilities *externally*. In this sense, the results show that the sampled companies use two different strategies. First, by *hiring skilled employees*, in case the training measures do not fill their lack of expertise. Despite recognising the difficulties in finding specialized employees, all interviewees stated that the knowledge acquired from skilled employees, whether in the technical or managerial field, is decisive to achieve sustained competitive advantage. For instance, company D mention: "*Skilled workforce is an important asset to remain competitive*".

The second way is through *innovative collaboration networks* beyond the company boundaries. All SMEs report that when they are not able to develop the necessary resources and capabilities internally, they establish interdisciplinary collaborations with external organizations. The type of collaboration used to access new knowledge and technologies does not vary within the sample. All cases highlight that they have *collaborations with universities and research institutes* (company B says: "*We work with trainees from universities; which is a way to integrate and share knowledge*")*; with Government and institutions* (company A: "*For instance, Portugal Government is providing great incentives to SMEs – Portugal 2020 program – investing in innovation and innovative products with competitive advantage*")*; and with customers and suppliers* (company B: "*We have suppliers who provide solutions* *according to our real needs*"). Such innovative collaboration networks aim to acquire know-how, licences or even purchase the technologies needed. In this regard, companies A, D and E report that they constantly develop new products with partner companies and emphasize that "*support from government programs is crucial*". They highlight that the success of customer/supplier engagement must lay in transparency and trust-based relationships in order to mitigate risks and drive growth for all parties involved. The results are summarized in Table 9.

Table 9. Resources and capabilities development in Portuguese SMEs

	Means of acquiring or developing R/C	**Excerpt of the interview responses**
Internally	• R&D oriented to new digital technologies	*"Most of our skills are developed by studying, researching and betting on ourselves..." (company B)*
	• Advanced human management practices (training)	*"To provide training to our employees is the best way to integrate ourselves into this evolution." (company B)*
	• Top management commitment	*"...employees were used to working with fully manual machines. When we moved to the new plant, where some tasks were automated, they showed some reluctance, but they got adapted over time." (company E)*
Externally	• Hiring skilled employees	*"Skilled workforce is an important asset to remain competitive." (company D)*
	• Innovative collaboration networks	*"We make partnerships with universities when it is necessary to develop new products or use its laboratories." (company A)*

3.6. Discussion

Based on the experience of five SMEs from Portugal this section aims to answer *RQ2: what are the resources and capabilities for Industry 4.0 implementation in SMEs?* and *RQ3: how can these resources and capabilities be acquired and/or developed?* Moreover, drawing on both RBV and dynamic capability theory, it seeks empirical evidence on how SMEs use resources and capabilities to create sustained competitive advantage.

3.6.1 Resources and capabilities for Industry 4.0 implementation in SMEs

The empirical results allowed to identify the key resources and capabilities needed to successfully implement Industry 4.0 in the Portuguese SMEs under analysis.

Within the ***technological dimension***, technological resources such as sensors, *RFID* and *QR code* are the most required by the SMEs under analysis. These technologies are being deployed mainly to monitor and control production processes through data gathering and in line with the survey results presented by Masood and Sonntag (2020), these technologies have greater benefits for the challenges incurred. By increasing the visibility of real-time data, the interviewed SMEs expect to improve their decision-making processes and then performance dimensions such as quality and lead-time.

Cloud computing is another resource identified with high frequency within the sample. However, even though the literature has been focusing on opportunities offered by cloud platforms such as new business models and servitization (Rymaszewska *et al.*, 2017; Culot *et al.*, 2020a), none of these Portuguese SMEs are using cloud as a *service*; instead, in most cases, cloud computing solutions are used to assist data storage and data sharing. Similar results were obtained by Moeuf *et al.* (2018); Müller *et al.* (2018) and Frank *et al.* (2019). In this regard, SMEs mostly focus on providing customized products/solutions. Therefore, as they are usually requested directly by customers who are looking for very specific solutions, the use of online platforms to reach customers have not attracted significant attention so far and could be a great opportunity for SMEs when deploying Industry 4.0 technologies.

As far as the risks of shared information is concerned, most of the respondents trust that *cybersecurity* is already provided by cloud computing, which is aligned with the results found by Moeuf *et al.* (2018). In fact, it seems that despite they recognize the importance of this resource, SMEs often underestimate the risks related to choosing a cloud-based solution that does not provide reliable levels of security (Moeuf *et al.*, 2020). As such, they stated that additional technical and legal approaches are needed to protect confidential information of systems and employees against cybercrime.

The (management) information systems, *Enterprise Resource Planning (ERP)* and *Manufacturing Execution System (MES)*, already broadly adopted by large enterprises, also appear as critical resources, as they allow storage and sharing of information, enabling horizontal and vertical integration. Although, on the one hand, they may be characterized as “old” technologies (Culot *et al.*, 2020a), and sometimes can be extremely rigid and expensive for SMEs, on the other hand, it seems that for these SMEs, they are the previous step to implement more complex systems such as cyber-physical systems (Müller *et al.*, 2017). As stressed by Moeuf *et al.* (2020), most SMEs are investing in less complex and less expensive technologies, since the employment of the most revolutionary Industry 4.0 technologies and interfaces (e.g., CPS, machine-to-machine communication, advanced robots, Big Data) imply higher costs and the return of the investments in the long term.

In the same vein, while user-friendly technological resources, such as *mobile technologies* (e.g., tablets and smartphones), that aim to simplify the employees' work allowing them to access the right information at anytime and anywhere, were identified with high adoption among the sample, more complex and expensive such as *additive manufacturing*, *CPS*, *M2M*, *SRM* and *augmented/virtual reality*, have instead not been implemented yet. This remarks again the importance given by SMEs to adopt low-cost solutions to follow the Industry 4.0 initiatives as was emphasised by Schneider (2018).

Concerning the ***organizational dimension***, the analyzed SMEs agree about the importance of all the 9 resources and capabilities that appear in this group. Furthermore, the SMEs in the sample are taking advantage of their experience in applying Lean Management practices in order to simplify Industry 4.0 requirements and thus facilitate their implementation process. Agostini and Filippini (2019) suggest that managers should adopt a Lean philosophy to open their firm boundaries to lay the foundations for an I4.0 factory. As such, *top management commitment capability* – a well-known Lean practice – is being used to communicate and support employees regarding the Industry 4.0 objectives. This closer relationship with the manager favours the development of digital culture among employees, that is an imperative capability in Industry 4.0 environments. Unlike the results found by Müller *et al.* (2018), it seems that the sampled SMEs do not lack managerial support.

Advanced human resource management practices such as training, are also among the necessary organizational resources and capabilities to implement Industry 4.0. The SMEs in the sample are being driven to offer in-house training to improve their employees' digital skills and ensure that they fit into the Industry 4.0 ecosystem. This result contrasts the evidence presented by Mittal *et al.* (2018a) who suggest SME staff are more likely to lack the exposure to mentors, workshops, supervised and industrial training if compared to larger companies.

Moreover, they seem to have a consensus on the importance of having a resource like an *IT structure*. *IT structures* are the means by which to produce information that is critical to developing other levels of capabilities like the *alignment between departments* (R&D, quality, production, etc.). In addition, a shared, flexible, and robust IT structure allows to align operations with real-time data and, thus, increases the company's ability to process information for better decision-making (Irfan *et al.*, 2019). Lastly, the sampled SMEs highlight that exploration of capabilities like *knowledge decision-making techniques* give them flexibility to meet the ever-changing customer habits and preferences (Kamble *et al.*, 2019; Moeuf *et al.*, 2020).

Within the ***external dimension***, the SMEs demonstrate to be very interested in exploiting capabilities such as *innovative collaboration networks*. Such networks can arise from the most varied players, for instance, consultants, governmental institutes, research centres and industrial partners (customer/supplier) and bring cost-efficient solutions for all parties involved. For instance, by providing a customized customer experience, SMEs can meet customer's individual requirements and increase customer satisfaction (Sony, 2018). In this sense, Mittal *et al.* (2018a) suggest that SMEs may have a deficit in (national/international) cross-disciplinary networking opportunities and emphasize that collaboration strategies are crucial to the success of SMEs.

Furthermore, the results highlight the importance of resources such as *financial incentives* and *industrial polices and standards*. These resources are critical to supporting SMEs in developing and implementing the Industry 4.0 resources and capabilities (Müller *et al.*, 2018; Moeuf *et al.*, 2020). Moeuf *et al.* (2020) add that although SMEs have some weakness in terms of financial resources compared to large companies, Industry 4.0 are now accessible to SMEs and they have all the means to overcome it. Against Mittal *et al.*, (2018a), the sampled SMEs do not fear investing in Industry 4.0. Contrarily, they fear losing markets if they do not fulfil the requirements of Industry 4.0. Müller *et al.* (2018) found similar results in a study conducted with German enterprises, where they identified a group of SMEs that are very interested in profiting through Industry 4.0. The authors referred to these SMEs as 'proactive SMEs'. The companies analyzed in this study might therefore belong to this group of SMEs.

Table 8 also indicates that *new business models* were not listed by any of the companies under analysis. A lack of awareness has been remarked by the respondents as the main cause of this result. This issue has been highlighted by Frank *et al.* (2019).

While the literature review identified 33 resources and capabilities to implement Industry 4.0 in SMEs, the empirical results suggest that, within the sample of companies under analysis, not all these resources and capabilities are required. In this sense, the Portuguese SMEs prioritize resources and capabilities that enable realtime data collection and facilitate connectivity. Indeed, Industry 4.0 technologies have increased the number of available data sources and, therefore, have become more attractive to SMEs, since the exploration of real-time data provides a more streamlined flow of information, allowing synchronized and optimized production process, customizing products and better connections with business partners (Moeuf *et al.*, 2018). In this sense, Moeuf *et al.* (2020) argue that SMEs should pursue resources and capabilities that might give them competitive advantage. In fact, the future of SMEs will increasingly depend on their ability to manage their value chain responsively, while gaining competitive advantage in their market (Schumacher *et al.*, 2016; Moeuf *et al.*, 2018). To achieve this, SMEs need to seize the opportunities available in order to get the best possible results with minimum resources (Faller and Feldmüller, 2015). In this regard, although the RBV theory draws attention to firm's resources as drivers for competitive advantage, not all firm resources can generate sustained competitive advantage. As mentioned before, to hold this potential a firm resource must have four attributes: value; rareness; inimitability; and non-substitutability (Barney, 1991, 2001). Scholars of RBV emphasize, however, that is the use of these resources and capabilities and not just their existence that will create sustained competitive advantage (Teece *et al.*, 1997; Wang et al., 2015).

Valuable resources and capabilities are related to firm's ability to implement strategies that are appropriate to the market in which it operates. Particularly, these strategies should be able to generate value in both strategic (e.g., exploiting external opportunities and/or reducing threats) and economic terms (e.g., increasing profits and/or reducing costs) (Barney *et al.*, 2012). Nevertheless, despite valuable resources and capabilities are considered necessary, they are not a sufficient condition for a firm to achieve superior performance. In this sense, having established the *value* of the aforementioned resources and capabilities, the other three attributes will now be discussed.

Regarding rareness, if a firm's valuable resource is unique among a firm's current and potential competition, this resource is considered rare. In this sense, while some technological resources (e.g., technologies and interfaces) can be easily acquired by competitors, since they are already accessible to SMEs with reasonable costs, others, such as the organizational resources and capabilities (e.g., top management commitment, digital skills, digital culture and innovation), that hold a sociotechnical character, could be considered rare. In this regard, Barney (1991) explains that for implementing some strategies, a particular mix (bundles) of resources and capabilities will be required. It means that in some cases, rare firm resources must be combined with other valuable firm resources and capabilities in order to implement value creation strategies. For example, the top management commitment capability will involve particular capabilities, such as the communication skills of the manager, the ability to involve employees throughout the company, manager's experience, organizational knowledge and so on, to exploit its potential of reducing failure risks and increasing quality and productivity. Such elements can only be developed through a complex and subjective learning process and therefore could be considered rare. The same argument might apply to digital skills, digital culture and innovation capabilities.

Nonetheless, Barney (1991) highlight that valuable and rare firm resources can only be sources of sustained competitive advantage if they are also inimitable. It means that if firm's resources and capabilities are rare and difficult or costly to imitate, they can be considered "strategic" and then can assure a sustainable competitive advantage (Barney *et al.*, 2012). In this regard, despite most cases suggest that some resources and capabilities could be easily copied (e.g., technological resources), the full exploration of such resources often involve complex social relations that are not easy to duplicate. Examples are the interpersonal relationships between managers and employees (e.g., top management commitment capability) or their relationships with business partners (e.g., innovative collaboration networks capability). These relationships are fundamentally based on mutual trust and they do not only involve the individual characteristics and the skills of the actors, but also depend heavily on the specific SMEs context, making it difficult, or even impossible, to imitate.

As far as the non-substitutability is concerned, a resource is non-substitutable when there are no equivalent resources that enable a firm to conceive and implement the same strategies, efficiently or effectively as the original resource (Barney *et al.*, 2012). Barney (1991) emphasizes that non-substitutability is also a matter of degree. This means that if a large number of firms have valuable substitutive resources, the strategies related to these resources are not rare and, therefore they will not be sources of competitive advantage. However, if a small number of firms have these valuable substitutive resources, then these firms may create sustained competitive advantage (Barney and Arikan, 2001). Therefore, as the interviewed SMEs highlight the importance of acquiring valuable and rare resources and capabilities that also hold properties that are difficult to imitate, these SMEs still may create sustained competitive advantage, since the empirical results indicate that they have few competitors operating within their business markets. However, Barney *et al.* (2012) draw attention to the fact that if resources and capabilities are not used properly in organizational terms they risk remaining only potential without being implemented.

3.6.2 Resources and capabilities development for Industry 4.0 implementation in SMEs

A typical issue in strategic management research is how firms can acquire and/or develop resources and capabilities in scenarios characterized by uncertainty in markets or customer demands (Clark and Iansiti, 1994; Teece *et al.*, 1997; Makadok, 2001; Lasi *et al.*, 2014). The dynamic capability theory addresses this issue, emphasizing the importance of considering the dynamic nature of capabilities to meet the requirements of the external environments (Wernerfelt, 1984; Teece *et al.*, 1997). As such, the results will be discussed through the lenses of the *dynamic capability theory*.

The findings of the empirical investigation suggest that the resources and capabilities required to implement Industry 4.0 in SMEs can be acquired and/or developed in two different ways, ***internally*** (e.g., *R&D oriented to new digital technologies, advanced human resources practices and top management commitment*) and **externally** (e.g., *hiring skilled employees and innovative collaboration networks*). Following *Wang et al.* (2015), this study argues that these two ways can be considered the mechanisms that dynamic capabilities use to rebuild firm's resources and capabilities in order to create sustained competitive advantage.

Regarding to the ***internal mechanism***, the results suggest three ways in which they can acquire and/or develop the resources and capabilities that they do not have. The first mechanism, *R&D oriented to new digital technologies* will involve dynamic capabilities such as *innovation* and *management of knowledge skills*. Such capabilities will contribute, for example, to new product developments, product design and new processes developments. Contrary to the general conclusions reported in the literature, all five SMEs are striving to perform well in R&D, aiming to develop innovative resources and capabilities that can differentiate them from the large companies (Mittal *et al.*, 2018a). In particular, Portuguese SMEs from the automotive sector (companies A and B) remarked their commitment with R&D. However, company cases suggest that there is still a lack of dedicated resources for research and development in Industry 4.0 technologies in SMEs, which is supported by Kumar *et al.* (2020). The second one, concerns the necessity of top management *commitment*. About this mechanism, empirical results suggest *digital culture* as the main related dynamic capability, since it will allow employees to develop new capabilities such as interdependent knowledge, problem solving and autonomy. Previously, Henderson and Cockburn (1994) have already stated that the dominant values (culture) of the organization will shape the development of new competences and capabilities. Fatorachian and Kazemi (2018) add that it is important to support not only the technological structure of the company, but also the cultural structure supporting the adoption of intelligent production systems. The third internal mechanism is *advanced human resources practices*. In this case, *training* is the mechanism that dynamic capabilities, such as *new digital skills* use to reskilling and upskilling employees. Similar results were found by Moeuf *et al.* (2020) who argue that while training may take more time than working with skilled consultants, the knowledge transfer processes are more accurate by using training mechanisms. It supports the results of this study when it establishes the importance of regular employee training for implementing Industry 4.0. However, according to Rauch *et al.* (2019), SMEs lack access to the financial and educational resources to ensure that Industry 4.0 is fully realized.

In addition, the efforts made by the SMEs to upskill their employees internally are sometimes not sufficient to develop the resources and capabilities needed. In these cases, they rely on ***external mechanisms***. The results suggest two ways whereby resources and capabilities can be developed: *hiring skilled employees* and *through innovative collaboration networks*.

Hiring skilled employees was reported by all SMEs as a critical mechanism to support any Industry 4.0 project, since they are key elements in the development of resources and capabilities for the technological, organizational and external dimensions. However, while, on the one hand, the *know-how* and *experience* (dynamic capabilities) of skilled employees are often considered decisive in creating sustained competitive advantage, on the other hand, the SMEs under analysis report having great difficulty in finding experts in certain domains. This absence of adequately skilled workforce is also referred by studies such as kamble *et al.* (2018). In addition, hiring skilled employees generally implies high financial resources that they are not willing to pay, since they would have other more innovative and less expensive options.

In line with this, one of the possibilities to fill the lack of expertise would be by establishing *innovative collaboration networks*. The SMEs emphasize that making innovative collaborations beyond company boundaries offer great advantages for SMEs. This agrees with Henderson and Cockburn (1994) and Wang *et al.* (2015) that stress external collaboration as an important mean to achieve sustained competitive advantage. Wang *et al.* (2015) add that in order to transform the firm's resources and capabilities into competitive advantage, external collaborations require dynamic capabilities such as *innovation*, *enhanced communication*, and *relationship* *capabilities*. According to them, *innovation capabilities* improve the capacity of the firm to develop resources and capabilities for greater competitive advantage; *communication capabilities* facilitate the exchange of information and transparency with partners and therefore enhance decision-making processes; and, lastly, *relationship capabilities* help companies develop, manage, and design their relationships with partners (Wang *et al*., 2015).

In this regard, the analyzed SMEs identified three main types of *innovative collaboration networks*, such as collaboration with *universities and research institutes*, with *government and institutions* and with *customers and suppliers*. Contrary to the results of Mittal *et al.* (2018a), the Portuguese SMEs under analysis are significantly cooperating with *universities* and *research institutions*, regardless of their size. They attribute this choice to two factors: First, *universities and research institutions* have advanced and updated know-how, although Moeuf *et al.* (2020) advert that when it comes to Industry 4.0, sometimes the practitioners are more advanced than universities. Second, the costs involved in such collaborations are much lower than hiring skilled employees or relying on consulting firms (Jäger *et al.*, 2016; Heberle *et al.*, 2017). Moreover, the Portuguese SMEs highlight that they take advantage of the strong support being provided by the *Portuguese Government*. This support is important for SMEs not only because of the financial incentives available (e.g., through Portugal 2020 program and other international/national initiatives), but also because of the fact that the Government plays a pivotal role in developing regulations and standards. As stated by Müller *et al.* (2018), the diversity of technologies, interfaces and platforms related to Industry 4.0 concept needs to be accessible for SMEs, but in a secure and efficient way. Several authors have already observed a lack of standards and government regulation across the industries embracing Industry 4.0 (kamble *et al.*, 2018; Raj *et al.*, 2020), these also include SMEs.

Finally, the interviewed SMEs establish innovative collaboration networks with *customers and suppliers* to develop customized products and innovative solutions. According to Rauch *et al.* (2019), it is important to ensure that the SME has a culture that includes customer and supplier needs through discourse and communication to allow for the full and productive integration of Industry 4.0 initiatives. Indeed, the five SMEs under analysis appear to be very clear about the importance of collaborative mechanisms as a driver to product development and business process innovation, and therefore, for creating sustained competitive advantage.

3.7 Conclusions and future research directions

This chapter aimed to identify the resources and capabilities that SMEs need to effectively implement Industry 4.0 and to exploit how SMEs can acquire and/or develop them. By doing so, it provided a comprehensive list of 33 resources and capabilities from extant literature. Thereafter, these resources and capabilities were validated by analyzing the experiences of five Portuguese SMEs. Lastly, the findings were analyzed through the lenses of resource-based view (RBV) and dynamic capabilities, in order to seek empirical evidence on how SMEs use resources and capabilities to create sustainable competitive advantage. The literature review highlights that these issues have not been fully addressed in previous research.

The results have shown that the resources and capabilities to implement Industry 4.0 in SMEs are already accessible to them with reasonable costs and efforts. Nonetheless, not all 33 resources and capabilities previously identified in the literature review are being required by the companies examined. In fact, the results suggest that SMEs implement Industry 4.0 balancing their specific needs with the affordable resources and capabilities, while focusing on the resources and capabilities that help them to achieve sustained competitive advantage. In this sense, the five Portuguese SMEs prioritize resources and capabilities that enable real-time data collection and facilitate connectivity. It might be concluded that one of the reasons for this choice is to improve decision-making processes, since better decision-making processes allow faster reaction to market changes, which is a crucial capability to create competitive advantage, especially in high uncertainty environments. Moreover, they recognize the importance of combining the technological, organizational, and external resources and capabilities to increase value creation and boost industrial performance. In this sense, the five SMEs take advantage of their experience applying Lean Management practices such as top management commitment, in order to help employees in the development of new capabilities such as digital skills and the digital culture, both considered by them as key capabilities for Industry 4.0 initiatives. In addition, they are strongly promoting innovation and customization capabilities to differentiate themselves from large companies. However, although the literature in Industry 4.0 underline several innovation opportunities that raise from new business models (Culot *et al.*, 2020a), those SMEs have not yet explored it.

Regarding how SMEs acquire and/or develop the necessary resources and capabilities to implement Industry 4.0, the results suggest that the Portuguese SMEs are also betting on their innovation capabilities. On one hand, they develop the resources and capabilities internally, for example, through R&D, top management commitment, and making use of training mechanisms, and on the other hand, they search for it externally, through hiring skilled employees and establishing innovative collaboration networks. Collaboration capabilities are increasingly important to create competitive advantage and it is one of the focuses of Industry 4.0 (Santos *et al*., 2018; Cimini *et al*., 2020).

This chapter therefore contributes to operations management theory by highlighting a set of 33 resources and capabilities to implement Industry 4.0 in SMEs. It also contributes to the RBV and dynamic capabilities theories by showing empirical evidence on how SMEs use Industry 4.0 resources and capabilities to achieve sustained competitive advantage. In this regard, this is one of the first studies to carry out an analysis of the resources and capabilities for Industry 4.0 implementation in SMEs through the lenses of RBV and dynamic capabilities. The study also contributes to management practice by shedding light on how SMEs can approach Industry 4.0 in order to maximize its benefits. In addition, it can help managers understand the kind of resources and capabilities that have the potential for generating sustainable competitive advantages in Industry 4.0 contexts. This can be done through the evaluation of the resources that a firm possesses and that have the potential to generate sustainable competitive advantage and then exploiting those resources more extensively (Barney *et al*., 2012).

This chapter is however characterized by some main limitations. First, the research considers SMEs that are located in a particular geographical context (Portugal), which may have introduced some sociocultural and political biases to the conclusions. Future research may assess whether the findings are replicable in other countries. Second, this study considered a sample of five Portuguese SMEs. However, many studies in the operations management field also employed a multiple case study approach using five case companies (see Dieste *et al*. (2020), Mirzaei *et al*. (2021) and Iakymenko *et al.* (2020)). Third, despite the sample is composed by companies from three different sectors (automotive, automation and textile), they have similar strategies to reach markets and therefore use similar technologies to realise it. This may be the reason for the fact that the study does not find significant differences between the analyzed cases. Future investigations could verify the possibility of extending this results to other industrial sectors, characterized by more expressive differences regarding their market strategies. Nonetheless, this study is relevant because it shows a distinct group of SMEs in Portugal that is strongly committed to being successful in implementing Industry 4.0.

Chapter 4. Industry 4.0 and Lean Management Integration

This chapter presents the purpose, motivation, methodology, an overview in Lean Management, Industry 4.0 and Lean Management integration, the discussion of the results, conclusions, and future research directions.

4.1 Purpose

This chapter addresses RQ4, i.e., *how to integrate Industry 4.0 and Lean Management?* (See section 1.2). More in detail, it is aimed at: (1) to summarize the current literature on Lean Management (for a literature review on Industry 4.0, see chapter 2); (2) to conduct a semi-systematic literature review in the intersecting fields of Industry 4.0 and LM and identify the research streams in this discipline; and (3) to present and discuss real-world examples of Industry 4.0-LM integration in order to make explicit the best practices that were implemented by distinct industrial sectors such as automotive, paper, furniture, healthcare, apparel, and machine manufacturing.

4.2 Motivation

Manufacturing companies face the continual challenge of improving their processes and systems in order to deliver the required production rates of high-quality products, while minimizing the use of resources (EFFRA, 2016). Thus manufacturing is constantly evolving from concept development to new practices for the production of goods for use or sale (Esmaeilian *et al.*, 2016). In this context, approaches such as Lean Management and, more recently, Industry 4.0, have been developed to support manufacturers to reach their goals (Buer *et al.*, 2018; Pagliosa and Tortorella, 2019).

In the last four decades, Lean Management (LM) has been considered a major concept for improving the operational performance of companies (Shah and Ward, 2003; Ciano *et al.*, 2019). The main goal of Lean is to provide high-quality products and services at minimal cost and at the pace of customer demand through the systematic elimination of waste and deep involvement of the workforce (Shah and Ward, 2007; Bhamu and Sangwan, 2014). Lean originates from the Toyota Production System (TPS), in Japan, but has been adopted worldwide due to its wide range of tangible benefits, such as reduced human effort, inventory, space, defects, costs and delivery time (Ciano *et al.*, 2018; Matharu and Sinha, 2019). Driven by the success achieved by Toyota and many other Lean organizations worldwide, a growing number of companies have adopted LM practices to reach superior performance, reduce costs and gain an edge over competitors (Bortolotti *et al.*, 2014; Costa *et al.*, 2019).

Nonetheless, in recent years, the rapid changes in technology and strong market demand fluctuations are leading industries to undergo shifts in their operational and management systems. Even though LM has already proven its efficacy in various sectors (Danese *et al.*, 2018), its fixed sequence of production and fixed cycle times are not suitable for the mass production of highly customized products (Kolberg *et al.*, 2017). Moreover, today's manufacturing environments require new infrastructures capable of handling the increasing data volumes and real-time data availability (Ciano *et al.*, 2018).

In this context, the literature suggests that Industry 4.0 has the potential to overcome the challenges faced by LM (Kolberg *et al.*, 2017; Ciano *et al.*, 2020). Industry 4.0 is seen as the 4th Industrial Revolution that brings new technological opportunities to realize the vision of smart production (B. Wang *et al.*, 2016; Dalenogare *et al.*, 2018). It is based on the integration of intelligent machines, products, and processes into a digital network that will enable real-time data collection and analysis as well as the interaction between all actors of the value chain. Thus, Industry 4.0 is expected to improve existing major manufacturing practices in terms of productivity, quality and flexibility to meet market requirements (Kagermann *et al.*, 2013; Moeuf *et al.*, 2020). Nonetheless, a successful implementation of Industry 4.0 should take into account the initial situation of the companies from a technical and social point of view (Wagner *et al.*, 2017). In the last decades LM has been widely adopted not only within the automotive industry, where this management approach has emerged, but also in several other sectors such as healthcare, construction, services and so on (Jasti and Kodali, 2015). Thereby, implementing Industry 4.0 mostly means integrating technologies in companies that already apply LM principles and practices. Kagermann *et al.* (2013) add that achieving Industry 4.0 vision will involve a gradual process within a long-term project and, therefore, it is very important to preserve the value of existing manufacturing systems. Moreover, authors agree that the focus on people enabled by LM are strongly related to Industry 4.0, since the implementation of technologies alone cannot solve the problems rooted in mismanagement or disorganization (Smit *et al.*, 2016; Kinzel, 2017; Piccarozzi *et al.*, 2018; Satoglu *et al.*, 2018; Ciano *et al.*, 2019). In fact, the performance advantages achieved primarily by Toyota and then by many Lean organizations are strictly linked to the way these firms manage people (Womack and Jones, 1996). The human being is considered the core of TPS system and the cornerstone of creating value. In this sense, Toyota focuses on people development by training employees, growing leaders, and supporting customers and suppliers (Bortolotti *et al.*, 2014). Moreover, despite this aspect could be seen as secondary in an automated system like Industry 4.0, it is fundamental for its correct implementation, since Industry 4.0 will require new skills and behaviours from workers who will operate in this new technological environment (Piccarozzi *et al.*, 2018). Otherwise, firms may set themselves to failure as it occurred with many Lean organizations that paid little attention to human-related practices (i.e., soft practices) and focused mainly on implementing Lean tools and techniques (i.e., hard practices) (Hines *et al.*, 2004; Akmal *et al.*, 2020). By ignoring the importance of setting the right culture and the involvement of all individuals in implementing a new approach, firms may not be able to achieve sustainable increased performances in the long term and are at risk to conclude their projects without realizing the expected results (Costa *et al.*, 2019).

These facts have led to an increase in studies exploring ways to integrate Industry 4.0 with Lean Management (Tortorella and Fettermann, 2017; Bal and Satoglu, 2018; Buer *et al.*, 2018; Sony, 2018; Kamble *et al.*, 2019; Pagliosa and Tortorella, 2019; Ciano *et al.*, 2020; Rosin *et al.*, 2020; Shahin *et al.*, 2020). Even though LM is usually referred as a low-tech approach (Dickmann, 2007), many authors have confirmed the positive correlation that exists between these two approaches and their effects on improving performance (Tortorella *et al.*, 2018; Kamble *et al.*, 2019; Rossini *et al.*, 2019). In addition, both, Industry 4.0 and LM rely on decentralized control and pursue the same goals of increasing productivity and flexibility (Buer *et al.*, 2018).

Nevertheless, the systematic literature review (SLR) conducted by Pagliosa and Tortorella (2019) indicates that research in this subject is still immature, so it needs to be further developed. Particularly, studies deal with literature reviews on the topic (e.g., Buer *et al.*, 2018; Pagliosa and Tortorella, 2019). Other studies address the impacts of Industry 4.0 solutions on LM practices through a theoretical length, and highlights "potential" benefits regarding an Industry 4.0-LM integration (e.g., Sanders *et al.*, 2016; Sony, 2018). Lastly, a third category of studies are focused on specific issues regarding Industry 4.0 and LM (e.g., R. Müller *et al.*, 2017 discusses the use of smart devices to support employees in SMEs). In fact, most research considers limited and specific aspects of an Industry 4.0-LM integration, with only few studies addressing a comprehensive set of technologies or practices (e.g., Mayr *et al.*, 2018; Ciano *et al.*, 2020; Rosin *et al.*, 2020). Hence, studies that explore best practices and provides applicable examples of an Industry 4.0-LM integration are still missing in the literature

(Wagner *et al.*, 2017; Powell *et al.*, 2018; Pagliosa and Tortorella, 2019; Shahin *et al.*, 2020).

Building thereon, this chapter aims to answer *RQ4: how to integrate Industry 4.0* and Lean Management? by presenting and discussing 6 real-world examples where Industry 4.0 technologies and LM practices have been combined and applied into distinct sectors (i.e., automotive, paper, furniture, healthcare, apparel, and machine manufacturing). This chapter took an approach similar to Shahin *et al.* (2020), who reviewed the existing literature on the link between Industry 4.0 technologies and Lean implementation and reported real-world examples for integrating these two approaches. However, in their study, only the integration of an Industry 4.0 technology (cloud) and a Lean tool (Kanban) is described in detail, limiting the transparency of the remaining examples. Further investigation of best practices in the simultaneous implementation of Industry 4.0 technologies and LM practices can guide practitioners towards a better understanding of the implementation outcomes and, therefore, can be useful in their decision-making processes.

4.3 Methodology

This chapter conducts a semi-systematic literature review (Snyder, 2019) in the intersecting fields of Industry 4.0 and LM. The purpose of a literature review is to objectively report the current knowledge on a topic based on published literature (Green *et al.*, 2006). This research method is different from the others because it is carried out without collecting and analyzing any primary data (Paré *et al.*, 2015). By using numerous sources, the authors search in the literature a vast amount of information that can serve to create new insights and, thus, provide new conclusions for the literature. As such, besides the aim of synthesize a topic, a literature review may be an excellent way for developing something that is new and valuable, and make a substantial contribution to the respective area of research (Snyder, 2019). There are many examples of papers published in management and business journals using a literature review strategy as a basis (e.g., see Aloini *et al.*, 2007; Mccoll-kennedy *et al.*, 2017; Esmaeilian *et al.*, 2018).

In this context, to answer the RQ4 and advance the current body of knowledge in the intersecting research domain of Industry 4.0 and LM, this chapter explores the synergic relationship between Industry 4.0 and LM. It does so by identifying six examples of real cases that address Industry 4.0-LM integration. The goal is to make explicit the best practices that have been implemented in six distinct industrial sectors such as automotive, paper, furniture, healthcare, apparel, and machine manufacturing. As such, this chapter uses an adapted version of the procedures proposed by Savaget *et al.* (2019), which results in a two-stage process called the sampling stage, and the analytical stage. The search was conducted using two databases: ISI Web of Science and Scopus. These databases were chosen due to their consistency in the indexing content. To reach the purpose of this study, the Boolean expression "Industry 4.0" AND "Lean" was used in the title, abstract, and keyword search fields. Following Crossan and Apaydin (2010), the search was limited to papers written in English and published between 2015 and 2018. The decision to restrict the search to over these three years was made based on two factors: first, the research in Industry 4.0 and LM is relatively recent, since Industry 4.0 topic starts to be disseminated in 2011 by the German Government (Kagermann *et al.*, 2013). Second, due to the growing number of papers published from 2015, with an identified peak of publications in 2016 (Pagliosa and Tortorella, 2019).

The initial phase resulted in a sample of 147 documents. Then, duplicate papers were eliminated. Next, the titles of all documents were reviewed to eliminate those that were unrelated to the goals of this study. Thereafter, the abstracts were reviewed before proceeding to a detailed reading of the papers, which resulted in an initial sample of 24 documents. This initial sample was subsequently complemented by semi-structured snowballing (see section 2.1) to expand the literature, resulting in a final sample of 88 documents. Finally, in the analytical stage, it was employed the content analysis method. In addition, to ensure that all relevant publications were examined, this sample was complemented with emerging research in Industry 4.0 and LM fields. At this stage, the selection of publications was made based on suggestions from experts in the field and from scientific websites. Moreover, for each new publication read, the snowballing approach was used again. This adaptation on the review strategy was of great importance in ensuring that the appropriate literature was covered (Snyder, 2019)

4.4 Lean Management: an overview

This section aims to define the state-of-the-art of Lean Management literature. As such, it first presents LM's background to explore LM concepts, its related elements (i.e., principles, tools, and practices), and applications. In this sense, it pays special attention on the implementation of LM in SMEs.

4.4.1 LM's background

Lean Management (LM), arguably the most prominent manufacturing paradigm of recent times, originated in the Toyota Production System (TPS) led by Japanese engineers Taiichi Ohno and Shigeo Shingo (Womack *et al.*, 1990). Japan was devasted after the Second World War either in its military power and in its industrial complex, while the USA was emerging as a major world power. In face of the scarcity of resources and intense domestic competition in the automotive market, Japan needed urgently to recover but could not afford the massive investment to rebuild its facilities. That's when the heads of Toyota reformulated and adapted the ideas practiced by Henry Ford in USA. Thus, Toyota started to produce automobiles with half the human effort, half the manufacturing space and half the investment. In addition, it uses less inventory, results in fewer defects, and introduces a greater and ever-growing quality of products (Womack *et al.*, 1990).

In general, TPS aims to eliminate any kind of waste and inconsistency in the production system and consists of two pillars: Just-in-Time (JIT) and Jidoka (Ohno, 1988; Jasti and Kodali, 2015). Monden (1983) described JIT as a production system focused on the production of parts on demand. It means having the right parts, at the right time, and at the right amount. Thus, minimised costs by eliminating unnecessary stocks (Jadhav *et al.*, 2014). JIT also includes concepts such as small lot sizes, mixed model production, multifunction workers, preventive maintenance, and JIT delivery by suppliers (Monden, 1983). On the other hand, Jidoka (autonomation) means giving some intelligence to machines, allowing them to autonomously halt production when problems arise. Taiichi Ohno, the coinventor of the TPS, stated that processes should be automated and supervised by employees (Ohno, 1988). In fact, TPS is not only elimination of non-value activities of process but also means a system of continuous improvement (kaizen in Japanese) and respect-for-people (i.e., employees, customers, and supply partners) (Bhamu and Sangwan, 2014). Thereby, TPS focuses on the active participation of employees to improve the quality of products and services which questioned the bureaucratic structures of organization (e.g., top-down management structures) that had characterized many western companies (Hines *et al.*, 2011). As such, the economic success of Toyota in 1980s can also be assigned to the integrated application of TQM (Total Quality Management). TQM is a management approach that emphasizes continuous improvement, meeting customer requirements, and employee involvement and teamwork (Ross, 1993). These principles and ideologies globally known as Toyota Production System (TPS) were later re-articulated in a internal Toyota document called "The Toyota Way" (Lander and Liker, 2007).

However, it was thanks to the book *The Machine that Changed the World* written by Womack *et al.* (1990) that the term Lean became popular, describing the practices carried out by TPS that explained its increased competitive advantages at that time (Shah and Ward, 2003; Alkhoraif *et al.*, 2019). The modern term Lean was first used by Krafcik in 1988 (Holweg, 2007; Jasti and Kodali, 2015) in his Master's degree thesis at the Massachusetts Institute of Technology (Danese *et al.*, 2018). It was called Lean because uses less of everything compared to mass production systems. As such, TPS/Lean was viewed as a new manufacturing paradigm in alternative to traditional Fordism manufacturing model (Womack *et al.*, 1990; Hines *et al.*, 2004) and would conquer the world in the 90s, due to the merits and benefic results obtained through an efficient management. As such, in the early 1990s, Toyota was considered the most efficient car maker that produced the best quality vehicles in the world, overtaking America's General Motors (Stewart and Raman, 2007). Not surprisingly, TPS still holds the status of the world's biggest automobile manufacturer.

As it can be noted, TPS/Lean has undergone huge improvements during its journey over the last decades. This fact has proven that, although Lean approach is not free of questions and controversies, the methods of mass production employed since the beginning of the 20th century needed to be rethought through an innovative and flexible approach such as the approach proposed by Toyota. Toyota's accomplishment was truly brilliant, as it gradually found ways to combine the advantages of small production batches with economies of scale in manufacturing. However, the formulation of one of the most influential production paradigms of recent times was not only due to the entrepreneurial imagination of Toyota engineers, but instead to a combination of several ideologies that appeared prior to it (e.g., Fordism, JIT, TQM, and TPS) with the original ideas of those geniuses of the Japanese automotive industry. Thus, it can be said that Lean was neither entirely original nor entirely imitative, so that is essentially hybrid (Holweg, 2007).

4.4.2 Lean Management concepts

Over the years, LM has evolved becoming a managerial paradigm that can be implemented in different sectors and processes (Shah and Ward, 2003; Danese *et al.*, 2018). Danese *et al.* (2018) reviewed the contemporary literature on LM and concluded that the diversity of implementations and settings make LM literature heterogeous and fragmented (Bhamu and Sangwan, 2014). Hence, so far, there is no consensus on the definition of LM among authors. The lack of a common definition of the concept becomes clear from the numerous descriptions and terms that are used to define LM

(Womack *et al.*, 1990; Shah and Ward, 2007). In this sense, LM has been developed as a way, concept, approach, process, philosophy, set of principles, system, program, and paradigm (Bhamu and Sangwan, 2014). For example, Womack *et al.* (1990) describe LM as *a dynamic process of change driven by a systematic set of principles and best practices aimed at continuous improvement*. For Shah and Ward (2003) *LM is a multi-dimensional approach composed of highly inter-related elements and a wide variety of management practices, including Just-in-Time, quality systems, work teams, cellular manufacturing, supplier management, etc. that will work synergistically to create a streamlined, high quality system that produces finished products at the pace of customer demand with little or no waste*. Pinto (2009) defines LM as *a philosophy of leadership and management whose objective is the development of people, processes, and systems, and a focus on creating value for customers through the identification and systematic reduction of waste throughout the organization*.

In sum, it can be highlighted that LM is generally described from two points of view (Shah and Ward, 2007). On the one hand, LM is seen as a philosophy with its guiding principles and overarching objectives (Womack and Jones, 1996). On the other hand, it is described from a practical perspective, consisting of a set of management tools and practices that can be directly observed (Shah and Ward, 2003). The ambiguity exists because since its appearance LM have undergone a lot of transformations, causing confusion about what comprises LM and how it can be measured operationally (Shah and Ward, 2007; Bhamu and Sangwan, 2014). In this context, the book *Lean Thinking* published by Womack & Jones (1996) helped to understand Lean as a whole and oriented many organizations by distinguishing Lean Thinking at the strategic level and Lean Production at the operational level (Lewis, 2000; Hines *et al.*, 2004). Thus, LM, which in its initial phase focused on the application of tools at the operational level in order to achieve better quality, shorter delivery times, and reduced costs, starts a gradual evolution assuming a more integrative perspective, more focused on people and value creation processes (Womack and Jones, 1996). As such, LM organizations sought to understand customer value to provide perfect value to the customer through a perfect value creation process that has zero waste. Womack *et al.* (1990) define waste as any human activity that absorbs resources, but that does not create any kind of value. As can be noted the definition of waste is intrinsically linked to the concept of value. Indeed, a manner to recognize waste is to identify all actions, steps, materials and processes that customers (stakeholders) do not value nor recognize as useful and, therefore, are not willing to pay

(Pinto, 2009). These activities increase the consumption of resources and time and fall on the costs of products/services, making them more expensive than they should be.

Ohno (1988) categorizes seven major wastes that are recurrent in an organization, such as:

- Overproduction: it means producing ahead of what's needed by the next process or customer. It is considered the worst kind of waste since it obscures all the other six problems.
- Waiting: wasted time waiting for the next step in production. For instance, operators stand idle while the machines cycle, the equipment fails, the necessary parts do not arrive, etc.
- Transport or Conveyance: unnecessary movements of materials and products that adds no value to the product.
- Processing: adding more value to a product than is required by the customer or performing incorrect processing.
- Inventory: having more than the minimum stocks necessary for a precisely controlled pull system.
- Motion: unnecessary moviments by operators such as looking for parts, tools, documents, etc.
- Defects: additional efforts caused by rework, scrap, and incorrect information.

The value creation process is supported by five principles of Lean Thinking such as identify value (value can only be defined by the ultimate customer and should be expressed in terms of product family); map the value stream (identify all the steps in the value stream for each product family in order to eliminate all types of waste); create flow (creating a value chain with no interruption in the production process, so the product will flow smoothly toward the customer); establish pull (the pull approach determines that nothing is done until the customer orders it); and pursuit perfection (as organizations specified value, identified the entire value stream, made the value creation steps for specific products flow continuously and allowed customers to pull value from the company, they should begin the process again and continue until a state of perfection is achieved in which the perfect value is created without waste) (Womack and Jones, 1996). This five-step process of thinking serve as a guide for an effective LM implementation.

Furthermore, an interesting approach in LM implementation is its consideration as an interrelated system of hard and soft practices (e.g., Shah and Ward, 2007; Bortolotti *et al.*, 2014; Costa *et al.*, 2019). Hard practices refer to technical and analytical tools such as JIT, cellular manufacturing, reduced lot size, continuous flow, among others; while soft practices emphasize the organizational and human side in operations, being directly related to principles, managerial concepts, people, and relations (Larteb *et al.*, 2015). A study conducted by Bortolotti *et al.* (2014) found out that the greater use of soft practices will differentiate successful Lean organizations. Consistent with this argument, other studies have highlighted that soft practices such as employee training, teamwork, small group problem solving, top management and leadership, collaborative relationships with customers and suppliers, and a focus on continuous improvement philosophy are fundamental for achieving superior performance through LM and sustaining the performance in the long term (Hines *et al.*, 2004; Shah and Ward, 2007; Larteb *et al.*, 2015; van Assen, 2018; Costa *et al.*, 2019; Hernandez-Matias *et al.*, 2019). They argue that by using soft practices, it is possible to avoid employee resistance to change, which is common in several LM projects and often lead organizations to failure. In fact, the LM literature agrees that by educating managers, training employees, and involving customers and suppliers through more cooperative relationships; soft practices are crucial to create a more appropriate environment for impelementing LM hard practices and gain competitive advantage over competitors (Shah and Ward, 2003, 2007; Bortolotti *et al.*, 2014). However, it is important to note that these facts do not nullify the importance of LM hard tools, since they are also essential for an organization to be Lean (Bortolotti *et al.*, 2014).

4.4.3 LM tools, practices, and applications

The benefits achieved through LM approach contributed to intensify the adoption of LM among organizations (Danese *et al.*, 2018). At first, most applications focused on the manufacturing sector. In that context, LM applications – which had hitherto focused on the automotive industry, mainly due to the influence of the success of TPS – began to expand beyond the automotive sector (e.g., textile, construction, food processing, medical, electrical and electronic equipment, ceramics, furniture) and manufacturing process (e.g., supply chain management (SCM), product development) (Danese *et al.*, 2018). Moreover, its benefits encouraged its application in all types of organizational systems, such as healthcare, human resources, services, public administration, and higher education (Martinez *et al.*, 2016). This led to the development of a myriad of tools and methodologies aimed at different purposes and waste elimination (Green and Dick, 2001). In fact, LM tools/practices can be found under different names and some of them overlap with other tools/practices. Also, it might happen that a particular tool/practice has a different method of implementation proposed by different researchers (Pavnaskar *et al.*, 2003). The most reported tools/practices in the literature are Value Stream Mapping (VSM), Kaizen, Kanban, Pull Systems, Just-in-time (JIT), Total Productive Maintenance (TPM), Total Quality Management (TQM), Single Minute Exchange of Die (SMED), 5'S, Standard Work, Cellular Layout, Poka-Yoke (mistake proofing), and Heijunka (level scheduling) (Shah and Ward, 2003, 2007; Jasti and Kodali, 2015; Negrão *et al.*, 2017; Alkhoraif *et al*, 2019). Besides, many of them are used together in order to further enhance the performance of the system (Bhamu and Sangwan, 2014). This section, therefore, presents some of the LM tools that are considered relevant for this study.

JIT means producing only the necessary products, at the necessary time, in the necessary quantity (Gupta and Jain, 2013; Jasti and Kodali, 2015). Considered one of the pillars of TPS, the implementation of this tool allows to minimize wastes (e.g., waiting and transport), eliminate unnecessary stocks, improve product quality, and, ultimately, reduce the total production cost (Sony, 2018). Lean tools like Kanban, Heijunka, and, SMED are crucial in supporting any JIT system (Ma *et al.*, 2017).

Kanban is the Japanese word for “signal” and represents a production control system for JIT (Sugimori *et al.*, 1977). It refers to a simple system in which material movement between workstations in a production line is based on cards (Gupta and Jain, 2013). In the Kanban system, a supplier should only deliver resources to the production line when they are required, so that production area has only the minimum stock necessary to keep the processes together (Sugimori *et al.*, 1977). Also, Kanban plays a vital role in the implementation of pull production (Ohno, 1988; Sanders *et al.*, 2016).

Pull production is one of the fundamental principles of LM (Womack and Jones, 1996). In LM, an operation should be triggered on demand, which means that no good or service should be produced until the downstream customer requires it (Powell *et al.*, 2013). Unlike a push system that is forecast-reliant; a pull system is a control-oriented system that operates by receiving signals (Kanban) that more production is needed. In other words, it is the Kanban generated in the successive station that starts the operation of its predecessor (Sanders *et al.*, 2016). As a result, work-in-progress (WIP) inventory is minimized, creating a smooth workflow, and allowing employees to focus on tasks that truly add value to customers.

TPM is a holistic approach to maintenance that strives to maximize equipment effectiveness throughout its life, eliminates breakdowns, and promotes autonomous maintenance through the participation and motivation of all employees, from top management to shop-floor workers (Ahuja and Khamba, 2008). In general, TPM is intended to increase the competitiveness of organizations, focusing on proactive and preventive maintenance and combining good work practices, teamwork and continuous improvement (Cooke, 2000). Moreover, empowering employees and creating shared responsibility for equipment leads to greater equipment effectiveness, greater productivity, fewer breakdowns and defects, lower costs, reliable deliveries, as well as improved safety and improved employee morale *(Ahuja and Khamba, 2008; Sanders et al.*, 2016).

Statistical Process Control (SPC) refers to the statistical method applied for monitoring production process through the use of a control chart (Zhang, 2010; Tsai and Lai, 2018). By collecting sample data at various points in the process, quality abnormalities can be detected and corrected, ensuring that no defects are passed from one process to another (Shah and Ward, 2007; Sanders *et al.*, 2016). Thus, SPC is considered a vital tool in the drive to improve quality as it allows to reduce wastes, as well as provide cost-effectively products and services that meet customer needs *(Liu et al.*, 2001).

Kaizen is a Japanese word that means continuous improvement (Gupta and Jain, 2013). Bhuiyan and Baghel (2005) define continuous improvement as a culture of sustained improvement aimed at eliminating waste in all systems and processes of an organization. It involves everyone in a company (i.e., managers and employees) working together and applying different tools and techniques to achieve regular and incremental improvements in the manufacturing process (Bhuiyan and Baghel, 2005; Ciano *et al.*, 2020).

Standard work is a detailed representation and documentation of current best practices for producing a product or service. By defining the best practice of the work to be done it creates a standard for comparison and, thus, a foundation from which to improve. In such a sense, standard work is considered one of the most powerful Lean tools, as it forms the basis for continuous improvement (Miroslava *et al.*, 2016). The benefits include reduced wastes, costs, and a safe working environment for employees. Furthermore, when processes are standardized, employees have more free time that can be used for creativity and innovation (Sony, 2018).

Value Stream Mapping (VSM) is a popular graphical tool that allows to visualize and analyze the material and information flow within the process or value stream in order to identify waste (Mayr *et al.*, 2018). The main goal of VSM is to find the value-added and non-value-added activities contributing to the final product to identify opportunities for improvement in a future target state (Nash and Poling, 2008; Gupta and Jain, 2013).

Furthermore, the literature review shows that LM is often associated with other approaches and methodologies such as Agile, the Theory of Constraints (TOC), Six Sigma, MRP, ERP, and more recently, Industry 4.0 (Hines *et al.*, 2004; Sanders *et al.*, 2016; Ciano *et al.*, 2019; Pagliosa and Tortorella, 2019). For example, the implementation of LM with Six Sigma has gained much popularity in recent years, especially among SMEs (Gupta and Jain, 2013; Arcidiacono and Pieroni, 2018; Alkhoraif *et al.*, 2019). Six Sigma is a quality management tool focused on process variability reduction and standardization to improve customer satisfaction by collecting data and completing statistical analysis (Nabhani and Shokri, 2009). Considering the modern-day company context, IT technologies are also considered important support systems for LM implementation (Powell *et al.*, 2013; Alkhoraif *et al.* 2019). Powell *et al.* (2013) explored the functionality offered by a ERP system to support pull production in the context of SMEs and found that the systematic application of LM practices with ERP can improve the efficiency of the organization. Similarly, Tortorella and Fettermann (2017) carried out a survey in 110 companies of different sizes and sectors to examine the relationship between LM practices and the implementation of Industry 4.0 in Brazilian manufacturing companies. The study suggests that the integration of Industry 4.0 technologies into existing LM systems leads to improvements in operational performance, even though socioeconomic conditions are not as favorable as in developed countries (Tortorella and Fettermann, 2017). Therefore, as can be noted, from a strategic point of view, any concept/tool/practice that leverages the value provided to the end customer can be combined with LM.

4.4.4 LM implementation in SMEs

Regarding the implementation of LM in SMEs, the literature reveals that its adoption is still low compared to its implementation in large enterprises, even with SMEs making up the bulk of industries in many countries (Achanga *et al.*, 2006; Bhamu and Sangwan, 2014). Indeed, the path to becoming a Lean organization has never been easy and many SMEs struggle with implementing the desired Lean tools (Sanders *et al.*, 2016). In particular, studies have shown that LM has not been adopted by a large number of SMEs mainly because of the fear of the costs of implementation and its subsequent benefits (Panizzolo *et al.*, 2012; Bhamu and Sangwan, 2014). Achanga *et al.* (2006) argue that, in fact, the lack of funding prevents many SMEs from implementing LM tools and practices, for example, in hiring specialists, training the workforce, among other good improvement strategies. In this sense, Alkhoraif *et al.* (2019) add that there are many LM tools available (afordable) to SMEs that can help them on their Lean journey. VSM, Kanban, kaizen, TPM, 5S, and visual management are some examples of these tools. A research carried out by Panizzolo *et al.* (2012) in manufacturing SMEs in India found that companies achieved significant operational benefits through LM implementation. The study highlights that some successful critical factors were top management commitment and leadership, finance, skills, external support (e.g., from government, customers and suppliers), and organizational culture (Achanga *et al.*, 2006; Panizzolo *et al.*, 2012; Bhamu and Sangwan, 2014). These results are supported by Alkhoraif *et al.* (2019), who added to this list important successful factors, such as employee involvement and participation, supply chain integration, direct or good communication, personal experience, and technical factors. On the other hand, the use of the wrong tool, use of one tool to solve all the problems, lack of understanding, and poor decision-making process were considered the main reasons for failure within SMEs (Panizzolo *et al.*, 2012; Jasti and Kodali, 2015).

Finally, authors argue that SMEs have specific characteristics that could used as an advantage in the implementation of LM methods (Alkhoraif *et al.*, 2019). For instance, because SMEs usually have a less complex organizational structure compared to large companies, they are more flexibile to change with their manufacturing process. Moreover, SMEs are better able to provide customized products and services, which can also be used by them as a source of competitive advantage (Mittal *et al.*, 2018a). In conclusion, SMEs should explore the benefits associated with LM to provide products and services that are of value to customers and, then, to be able to prosper in global trade (Alkhoraif *et al.*, 2019).

4.5 Industry 4.0 and Lean Management integration

This section presents the research streams and the best practices in Industry 4.0-LM integration.

4.5.1 Research streams

The production systems of the current century now differ radically from their original forms. The changes wrought in individual and social values have affected not only products and service requirements but also the ways in which these products and services are manufactured. In this context, although LM has been successfully applied among various business domains, some factors restrict its scope (Kolberg *et al.*, 2017). One of them is dealing with strong deviations in market demands, caused by the need to satisfy customers that are constantly evolving. Although LM supports a greater variety of products, any change in production processes, batch sizes, and cycle times require laborious adjustments to Kanban cards (Dickmann, 2007). Consequently, the suitability of LM for shorter product life cycles and highly customized products is limited (Kolberg *et al.*, 2017). It was in aid of overcoming these barriers that the early 1990s saw the rise of the first approaches proposing to integrate automation technology into LM systems, later known as Lean automation (Jackson *et al.*, 2011). Curiously, over the years, companies that have made extensive use of automation were not considered to be Lean. The Toyota Production System in its purest form is completely independent of any kind of ICT, focusing on people rather than machines (Buer *et al.*, 2018). In fact, TPS and Lean methods have their origins in the 1950s and therefore do not take into account the possibilities offered by modern technologies. Nevertheless, in the early 1960s, Taiichi Ohno, the coinventor of TPS, had already stated that processes should be automated and supervised by employees (Ohno, 1988). This principle, known as autonomation (Jidoka in Japanese) (Ohno, 1988) is considered one of the major pillars of both TPS and LM systems. The concept means giving some intelligence to machines, allowing them to autonomously halt production when problems arise. Also, autonomation is an important part of the visual control in Lean systems, as it emphasises transparency, rendering the current state of production permanently visible and enabling faster reactions if problems occur (Jackson *et al.*, 2011). Therefore, for researchers in Lean automation the issue is not whether LM should be automated, but rather concerns the appropriate type and level of automation (Harris and Harris, 2008). In this sense, Industry 4.0 can offer new solutions for combining automation with LM approach (Kolberg and Zühlke, 2015; Kolberg *et al.*, 2017). Kolberg and Zühlke (2015) add that Lean automation attempts to integrate LM with Industry 4.0 to take the best from both worlds. In such a sense, it can be concluded that Industry 4.0 does not mean the end of Lean. Contrarily, literature recognizes the strong link between the two approaches (e.g., Sanders *et al.*, 2016; Buer *et al.*, 2018; Rossini *et al.*, 2019; Ciano *et al.*, 2020).

So far, authors have approached the integration of Industry 4.0 with LM from several perspectives. For instance, from a theoretical view, Sanders *et al.* (2016) identified the main challenges to implement LM from an integrative perspective and then highlighted suitable Industry 4.0 solutions to overcome these barriers. In doing so, the authors analyzed Industry 4.0 solutions for 10 dimensions of LM and grouped it into 4 LM factors (e.g., supplier, customer, processes, and control/human factors). The review conducted by Shahin *et al.* (2020) took a similar approach by enumerating specific LM practices and Industry 4.0 technologies that can be implemented together to address existing production challenges. Sony (2018) proposed an integration framework that takes into account the 5 LM based principles (define value, identify de value stream for each product/service, create flow, establish pull, and pursuit perfection) and the 3 types of integration proposed by Industry 4.0 (horizontal, vertical, and end-to-end digital integration).

Empirical studies have also been carried out in this discipline. For example, Khanchanapong *et al.* (2014) collected data from 186 manufacturing plants in Thailand and found that advanced manufacturing technologies (e.g., robots, real-time process control systems, and computer-aided manufacturing) and LM practices have unique effects on operational performance dimensions such as quality, lead-time, flexibility, and cost. The authors also highlight the complementary effects that organizational resources have on those performance dimensions. Tortorella and Fettermann (2017) carried out a survey in Brazilian manufacturing companies to investigate the moderating effect of Industry 4.0 on the relationship between Lean concepts (e.g., Pull practices, continuous flow practices, and low setup time) and operational performance. Kamble *et al.* (2019) investigated the relationship between Industry 4.0 technologies, LM, and sustainable organizational performance (SOP) in Indian manufacturing companies. These studies suggested that LM is positively associated with Industry 4.0 technologies and investing in both paradigms simultaneously can lead to better performance. Taking a different approach, Ciano *et al.* (2020) carried out a multiple case study research, in Italy, to examine the relationship between Industry 4.0 and LM through an one-to-one analysis in both directions, i.e., considering the enabling effect of LM on Industry 4.0 and the empowering effect of Industry 4.0 on LM. As a result, the authors proposed a comprehensive framework on the relationships between the two paradigms that include six areas of the value chain (e.g., manufacturing equipment and processes, shop-floor management, workforce management, new product development, supplier relationships, customer relationships) (Ciano *et al.*, 2020).

Given the above, three major research streams can be highlighted. In the first research stream Industry 4.0 is applied to support LM (Kolberg and Zühlke, 2015; Sanders *et al.*, 2016; Kolberg *et al.*, 2017; Ma *et al.*, 2017; Buer *et al.*, 2018; Mayr *et al.*, 2018). In such a sense, researchers argue that Industry 4.0 technologies can reinforce

LM practices by enabling the collection and analysis of important plant floor and management data and then providing solutions for the main causes of failure and inefficiencies in operations management, such as lack of accurate information and time-sensitive data (Chongwatpol and Sharda, 2013). Real-time data collection, for example, can support Lean tools/practices such as value stream mapping (VSM) and waste elimination (Mrugalska and Wyrwicka, 2017). Another worthwhile example is the eletronic version of kanban tool. In recent years, many companies have replaced traditional Kanban cards (i.e., Lean tool used for an order-oriented production control) by their electronic version known as e-Kanban. Depending on the implementation of the so-called eKanban, missing or empty bins are automatically recognized by sensors. The e-kanban reduces the likelihood of errors by eliminating human failure in filling kanban cards, i.e., by reducing bureaucratic tasks and excessive paper circulation. Thus, lost kanban no longer causes errors in production control, as long as the stock in the manufacturing execution system corresponds to the real stock (Kolberg and Zühlke, 2015). Even though the e-Kanban use technologies such as Radio-Frequency Identification (RFID) (Baudin and Rao, 2005), the tool remains rooted in the original concept of the Kanban. Lastly, LM also means a philosophy of continuous improvement (Kaizen), where Industry 4.0 can give the technological support to achieve excellence in manufactured products, processes, and the organization in its entirety.

On the other hand, the second research stream claims that a manufacturing system that has implemented LM is more likely to be modelled and controlled, which may create an optimal foundation on which to build a smart factory (Bal and Satoglu, 2018; Rossini *et al.*, 2019). In this sense, LM is an enabler for Industry 4.0 implementation. Indeed, production processes in LM are more standardized, more transparent and reduced to essential work when compared to other kinds of organizational systems. Thus, researchers claim that the low levels of complexity and emphasis on team working of LM systems can facilitate the automation of manufacturing processes and, ultimately, the implementation of Industry 4.0 (Kolberg and Zühlke, 2015). Besides, there is a general consensus in the literature that LM's focus on the human factor is critical for improving the quality of products and productivity (Kinzel, 2017; Peruzzini et al., 2017; Piccarozzi et al., 2018). For Frison (2015) Industry 4.0 may eventually render some Lean techniques obsolete, but in the meantime, it will also require Lean tools and practices to achieve better results. However, although the literature seems to recognize LM as a prerequisite for the implementation of Industry 4.0, there is still a lack of research in this direction (Buer *et al.*, 2018; Ciano *et al.*, 2020).

Lastly, a third research stream addresses the performance implications of an Industry 4.0-LM integration (Khanchanapong *et al.*, 2014; Tortorella and Fettermann, 2017; Kamble *et al.*, 2019). These studies usually focus on which performance metrics are affected through an Industry 4.0-LM integration (Buer *et al.*, 2018). Figure 5 illustrates these three reseach streams and their main characteristics.

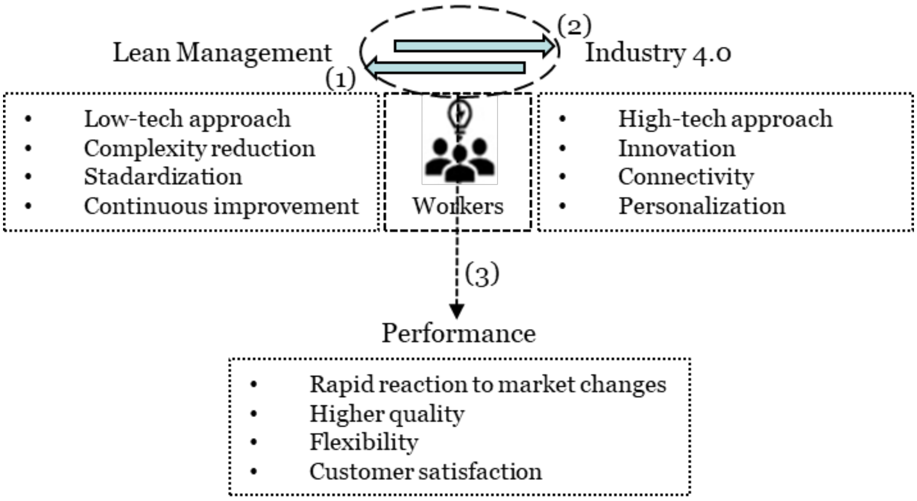

Figure 5. Industry 4.0-LM integration research streams (Santos et al., 2021)

4.5.2 Industry 4.0-LM integration: best practices from the literature

This section reviews the existing systems in which Industry 4.0 technologies and LM practices have been combined. The 6 real-world examples presented were taken from the extant literature in this discipline and aim to make explicit the best practices that were implemented by distinct industrial sectors such as automotive, paper, furniture, healthcare, apparel, and machine manufacturing. The studies discuss the factors that have to be taken into account while conducting this integration, as well as the advantages obtained over conventional manufacturing systems. In addition, in order to provide a better understanding of the different types of synergy that may arise from an Industry 4.0-LM integration and considering that both Industry 4.0 and LM approaches comprise a set of principles/tools/practices (in the case of Lean) and technologies/interfaces (in the case of Industry 4.0) that often require other tools or practices to fulfill their purposes, the examples were grouped into four key Industry 4.0 solutions, such as follows:

- Cyber-Physical Systems (CPS)
- Simulation
- Big Data Analytics and Data Mining

- Human-Machine Interfaces (HMI)

The choice of such structure was made based on the main integration objectives of each case.

Example 1 – Automotive Industry (cyber-physical systems)

Wagner *et al.* (2017) presented a "cyber-physical Just-in-Time delivery" to balance the material stocks in a global automotive company with an advanced level of Lean maturity. As the first step, a decision support framework called Industry 4.0 impact matrix was developed in order to provide an estimation of the impact of Industry 4.0 technologies on the well-established LM practices. Thus, the next step was to carry out an assessment of all LM processes at the company. Afterwards, the authors found a potential application in the process stability of Just-inTime (JIT) delivery for electrical assembly parts. Based on the proposed matrix, the Industry 4.0 solutions such as big data, data analytics, and vertical integration of machine to machine communication were identified as the solutions more likely to positively impact the JIT process. Thus, the next step focused on the implementation of these solutions. Since Kanban is the LM tool utilized to control JIT between workstations, the authors developed a cyber-physical application to replace the traditional Kanban cards by a vertically integrated solution based on machine to machine communication (M2M). It consisted in reducing the gap of information flow between manufacturing order, material delivery, material consumption, and material stock and the generation of an automatic purchase order to the supplier. At this point, a horizontally integrated solution was added by redesigning the database of the manufacturing execution system (MES). As such, it was also necessary to develop and integrate an additional JIT-service task on a middleware system. By using sensors, every material movement could be detected and posted in a big data architecture. Thus, when the material stock was reduced to a minimum stock level, an automatic purchase order for the supplier was generated. Moreover, the data related to the delivered material were automatically collected using an optical RFID system and considered in the forecast of material requirements. Finally, due to the increased level of traceability and process reliability, it was possible to reduce the warehouse space.

Example 2 – Paper Industry (cyber-physical systems)

Another example related to a CPS solution is given by Tsai and Lai (2018) who described a study case relating the benefits gained from the implementation of Industry 4.0 technologies in the paper industry. In their work, CPSs combined with other popular Industry 4.0 technologies such as IoT and sensors were used to monitor and quality control. In terms of the Industry 4.0 objective, given that in LM systems the availability and reliability of production equipment have an important impact on production efficiency and product quality, sensors were installed on the machines in order to track their status and detect abnormalities. This allowed collecting more accurate and reliable data to monitor equipment's performance. In this sense, the paper company uses vibration diagnosis in order to determine the deterioration of the bearings for preventive maintenance. The result was an increase of 15% in the machine operation rate and a decrease of 20% in non-performance. Moreover, before adopting Industry 4.0 technologies, the company used manual data collection and statistical analysis when using SPC method to control product quality. SPC uses statistical methods to measure, monitor, and control processes. The main problem was that the processing time was very long and then difficult to implement. Thus, the company applied IoT, PLC and MES for data statistics, analysis, monitoring, and transmission. Thereby, when the quality abnormality is detected, the monitoring system can timely transmit the information to the manager, who will take the appropriate measures to eliminate the anomalies, as well as adjust the production plan if necessary.

Example 3 – Furniture Industry (Simulation)

Rosienkiewicz *et al.* (2018) presented a study performed in the furniture industry in Poland. The company in question produced kitchen and bathroom furniture and primarily used an online marketing channel. The main goal of the study was to develop a Lean hybrid production system that incorporates Industry 4.0 technologies to provide a more precise production planning capable of maximizing the usage of workstations in unpredictable environments. The approach proposed by the authors was based on LM principles, Glenday Sieve, Artificial Neural Networks (ANNs), simulation modeling and was composed of a multi-stage process. In the first stage, the company was analyzed in-depth to gather historical data related to production volumes and customer orders. Thereafter, the Glenday Sieve method was used in order to classify the products into four groups, while the production forecast was estimated using ANNs. As a result, three different ways of manufacturing the products have been identified: (1) products could be manufactured using the sequential pull system, (2) the replenishment pull system, or (3) a separate production line could be built to satisfy individual and customized orders. Using the forecast results, an appropriate number of machines were set up and the simulation model was used to optimize the use of workstations and workers, identify abnormalities, and assess the reaction of the control system in relation to these factors. The results of the study confirmed that the proposed hybrid approach increased productivity while decreasing stock levels by reducing the number of incorrect forecasts. This was possible due to the introduction of an additional production line that was dedicated exclusively to unpredictable and customized orders. Lastly, the improved production planning has reduced delivery times to 48 hours for online sales. This was an important achievement for the company since this type of business model in Poland is still in development

Example 4 – HealthCare Industry (Big Data Analytics and Data Mining)

Arcidiacono and Pieroni (2018) demonstrate the advantages of applying LM and Six Sigma methods in light of the Industry 4.0 paradigm in the healthcare context. The integration of LM and Six Sigma has created Lean Six Sigma (LSS) (Arcidiacono et al., 2016). The Lean Six Sigma combines Six Sigma methodology with Lean Thinking and has already proven to be highly successful in a variety of sectors, including in hospitals. In fact, the growing demand for patient-oriented and more efficient health services has increased the application of LSS in the healthcare service. In this context, since most of the tools in this methodology are based on data for the purpose of investigating the root causes of problems in-depth, the authors argued that the integration of LSS and Industry 4.0 is an important area of research to be explored. Thus, they proposed a new methodology called "Lean Six Sigma 4.0" (LSS 4.0). The LSS 4.0 methodology aimed to optimize the supply services process and to reduce the waste of human and/or material resources while improving the Quality of Experience (QoE) of patients. Next, the processes involved in the admission of patients were evaluated using the LSS 4.0, which proved to be a valuable tool to provide more effective performance measures. More specifically, thanks to the technologies of Industry 4.0 it was possible to gather real-time data, enabling the continuous improvement of processes. For example, the registration of the specialist consulting activities in the hospital information system and the knowledge about the available beds in the ward were improved. Moreover, as IoT makes continuous feedback easier (e.g., through social networks), customer involvement has become even more important. Thus, customers' inputs could be collected and used to adjust processes in real time. In this sense, big data was a valuable tool providing information about the entire "customer experience". In conclusion, this case study shows that the integration of Industry 4.0 with LM and its related methodologies, such as Six Sigma, is not limited to the manufacturing industries, but also extends to other sectors, such as services and public administration.

Example 5 – Apparel Industry (Big Data Analytics and Data Mining)

Phuong and Guidat (2018) presented a study case of an apparel company where "Sustainable Value Stream Mapping" (SVSM) was used to explore potential sustainability issues in production processes. In addition, the authors also discussed the impact of employing Industry 4.0 technologies on process sustainability. They argued that despite the considerable body of research about extending VSM implementations and their proven benefits, its visual presentation does not share sufficient data about the processes. However, the authors point out that even though Industry 4.0 technologies are able to bring advantages related to real-time data tracking, a comprehensive Industry 4.0 system implementation could demand substantial investment. In this sense, they claim that a more feasible solution would be to employ a single technology instead of implementing automation wholesale. As such, they proposed the use of RFID tags. The implementation of RFID enabled the company to identify and eliminate significant sources of waste by improving the traceability of items. Thereon, the data gathered through the RFID system was stored in the ERP as a primary database, facilitating data mining. Data mining is the process of discovering anomalies, patterns, and correlations in large data sets and applying algorithms to extract hidden information and predict outcomes (Chen *et al.*, 2015). Thereby, a real-time SVSM could be properly tracked and displayed via a dashboard screen. In the end, an Excel file connected to the main database of the ERP system was used as a secondary database to provide a simple method to support data mining. Finally, aside from the presented advantages at the production and management levels, the SVSM supported by RFID tags has proved to be a great tool to support decision-making, allowing managers and engineers to detect potential issues related to the company.

Example 6 – Machine Manufacturing Industry (Human-Machine Interface)

In the Industry 4.0 era, human-machine interfaces are a determining factor mediating the interaction between workers and machines. From this point of view, Müller *et al.* (2017) presented a study based on the use of smart devices, such as Smart Pens, Tablet PCs and the development of a CPS production-APP called "shop floor information-application" (SIA) to support employees in SMEs. The goal is to integrate the shop floor and top floor departments of a special machine manufacturer by using LM methods for the digitization of information. At the factory in question, customized machines are designed in the company's design and development department. All subsequent processes are fulfilled on the shop floor. The main problem faced by the company was when drawing and construction mistakes occurred, so it was necessary to correct them, not only on the product but also on the technical drawings. In fact, as in SMEs, the transmission of information between business departments is often carried out in a paper-based way, any changes in components or changes in the technical drawings had to be rewritten by hand, which is labor-intensive, in addition to causing delays. Thus, the authors proposed a solution for SMEs to gather real-time information on the shop floor and distribute it to the organizational departments by combining LM tools with Industry 4.0 technologies. In this sense, by specifying requirements and elaborating a functional model, the authors developed six functionalities for the production-APP SIA. More in detail, after the employee logs into the APP, a QR-Scan is executed. In this phase, the employee moves the tablet over the QR-Code on the technical drawing, which allows its data to be downloaded, thereby, allowing the previously corresponding drawing to be viewed on the shop floor on the screen of the Tablet-PC. In the next step, the user chooses between four different functionalities, "Tablet Pen", "Take Picture", "Smart Pen", and "3D Model". Once the information related to the selected function has been transferred, the changes made to the technical drawing are sent to the design and development department using the "Send Email" function. The result of this implementation was a closed loop between the company's physical objects and its information system, enabling vertical integration. In addition, the best practice procedure can be used by other SMEs to develop their own production application, in order to connect production and business departments and share relevant information.

4.6 Discussion

This section discusses the results of the real-world examples presented above. Furthermore, in order to seek support on the current body of knowledge, the results are compared to previous literature in the field. Table 10 summarizes the results of the 6 real-world examples and emphasizes the main contributions of each one.

Regarding ***example 1*** (automotive industry), a CPS framework was developed to support LM practices by integrating physical materials, digital/virtual components, and employees. The main idea was to develop an IT system based on real-time data, capable of supporting Just-in-Time material flow process. This is in line with the outcomes of Ciano *et al.* (2020) that found that horizontal/vertical integration and smart machines integrated with MES and ERP systems can empower Lean practices such as JIT and kanban (Sony, 2018). For instance, the real-time tracking of material consumption makes the kanban system aware of the need for replenishment and automatically sends orders to suppliers. In this self-organized system, changes in schedules can be continuously monitored and kanban parameters can be updated, which leads to a significant reduction in stock levels (Kolberg and Zühlke, 2015; Sanders et al., 2016). In this sense, Mayr et al. (2018) add that when inventories are minimized, the use of warehouse space is reduced, resulting in cost savings. In addition, the increase in transparency makes the detection of bottlenecks in the production processes easier to identify. Finally, big data and analytics allow calculating KPIs in real-time that are displayed and transparent to employees, reducing the effort to update conventional Kanban boards and, consequently, allowing processes to be better controlled (Kolberg and Zühlke, 2015).

Table 10. Summary of the real-world examples and their main contributions

	#	Industry 4.0 solutions	LM Tool/practices	Contributions of an Industry 4.0-LM integration
CPS	(1)	• CPS • Sensors • RFID • Big Data Analytics • Vertical/Horizontal integration	• JIT • Kanban	• Deliver traceability • Processes' reliability • Increased efficiency • Reduction of warehouse space
	(2)	• CPS • IoT • Sensors • PLC • MES	• Performance's equipment • Statistical Process Control	• Improved equipment's performance • Predictive maintenance • Increased production efficiency • Enhanced quality • Reduced defect waste
Simulation	(3)	• Artificial Neural Networks (ANN) • Artificial intelligence (AI)	• Production scheduling and planning • Pull production	• Maximized usage of workstations • Decreased stock levels • Increased productivity • Reduced delivery time
Big data analytics/Data mining	(4)	• Big Data Analytics • IoT	• Six Sigma • Standard work • Customer involvement • Continuous improvement	• Reduced wastes of waiting • Enhanced customer experience
	(5)	• Data Mining • RFID • ERP • Vertical integration	• VSM • Waste reduction	• Traceability • Greater connectivity • Improved decision-making process
HMI	(6)	• HMI • CPS • QR code • Vertical integration	• JIT • VSM	• Traceability • Improved flow of information • Decreased waste of defects and extra processing • Reduced cycle time

Source: Wagner *et al.* (2017); Tsai and Lai (2018); Rosienkiewicz *et al.* (2018); Arcidiacono and Pieroni (2018); Phuong and Guidat (2018); Müller et al. (2017).

On the other hand, ***example 2*** (paper industry) used CPS to provide machines with self-awareness and self-predictive capabilities to enhance the equipment's performance. In LM, the availability and reliability of the equipment are considered critical factors, as production efficiency and product quality are strongly related to them. As such, the early detection, control, and prevention of equipment failures are of crucial importance to ensure safe and stable production in the factory (Tsai and Lai, 2018). In this sense, the authors argue that related Industry 4.0 technologies can bring tremendous benefits to machine maintenance and quality control in production, as also stated by Kolberg and Zühlke (2015) and Sanders *et al.* (2016). In the same direction, Ciano *et al.* (2020) found that IoT, horizontal and vertical integration can empower LM tools such as, Andon and Statistical Process Control, by detecting abnormalities in real-time and sending error notifications to the shop floor and maintenance personnel via smartphones, smartwatches or screens (Ma *et al.*, 2017). So, in case of failures, employees can be notified quickly, regardless of their location (Kolberg and Zühlke, 2015). Furthermore, the real-time awareness of the reliability and availability of the machines allows MES to reschedule tasks in a timely manner, which reduces the impact of breakdowns (Sanders *et al.*, 2016). In this sense, many authors have highlighted the importance of predictive capabilities for predicting maintenance actions as well as for planned maintenance (Lee *et al.*, 2013; Sanders *et al.*, 2016; Mayr *et al.*, 2018; Ciano *et al.*, 2020). According to Ciano *et al.* (2020), big data analytics is the Industry 4.0 technology that empower TPM, avoinding potential failures that could have significant impact on people, equipment, products, and the environment. Regarding product quality, example 2 supports the research carried out by Lee *et al.* (2013) who found that predictive technologies with intelligent algorithms can also predict product performance degradation and autonomously manage and optimize product service needs, avoiding the production of defective products.

As far as simulation technologies are concerned, ***example 3*** (furniture industry), combined a simulation model with LM principles, such as pull production to scheduling and planning production processes. This combination increased the system's resilience, which is crucial for systems operating under rapidly changing environments. In this context, the research performed by Ciano *et al.* (2020) shows that process simulation allows trying different layout configurations and can support Lean practices such as One-Piece-Flow and JIT. In this way, it is possible to reach an efficient layout configuration by evaluating parameters such as machine utilization, waiting time, and throughput obtained from various simulation experiments. Similarly, Mayr *et al.* (2018) highlight the importance of simulation methods in supporting kanban and TPM. According to them, simulation guarantees the identification of the optimal kanban parameters, such as lot size, stock or delivery frequency, as well as allows the consideration of external changes since the system update the parameters autonomously (Kolberg and Zühlke, 2015).

In ***example 4*** (healthcare sector), technologies such as IoT and big data analytics were used to increase data visibility and investigate the root causes of common problems in the healthcare service. By integrating these technologies with Six Sigma methodology and LM approach, the flow of information and resources could be optimized, which reduced the waste of waiting. In addition, the possibility to access and analyze real-time data allowed the continuous improvement of the whole process as well as it enhanced customer experience. Previously, Sanders *et al.* (2016) pointed out the importance of RFID, IoT, and advanced analytics for the Six Sigma approach because of their potential to improve traceability, visibility, and memory.

Still regarding the exploration of data, ***example 5*** (apparel company) used data mining, RFID and ERP to enable vertical integration and reduce the gap of information. These Industry 4.0 solutions were implemented along with a VSM tool, in order to identify wastes and support the decision-making process. This is in line with the scientific works of Kolberg *et al.* (2017), Mayr *et al.* (2018), Sony (2018) and Ciano *et al.* (2020). Mayr *et al.* (2018) argue that the main benefit of the combination of VSM with Industry 4.0, which they call “VSM 4.0”, is increased transparency due to the real-time display of value streams. Not only does this help in identifying waste, but also improves the decision-making process as decisions are based on real-time data. In this context, Sony (2018) states that before creating an integrated environment through Industry 4.0, it is important to define the value-adding activities to identify and eliminate waste within the organization. Similarly, Ciano *et al.* (2020) suggest that the VSM allows for the vertical integration of manufacturing processes, as it helps to identify pivotal areas and processes in which Industry 4.0 should be considered (Sony, 2018).

Finally, ***example 6*** (machine manufacturing industry) developed an ergonomic human-machine interface to support employees in receiving, transmitting, and documenting the correct information, as failures in communication can lead to adverse effects on the schedule of production as well as the morale of employees. Once employees play an important role in the acceptance and implementation of any technological change, user-friendly technologies are critical to empowering employees, enabling them to perform their roles more efficiently. The result was a significant reduction in important sources of waste, such as defects and extra processing and the overall cycle time. This supports the research developed by Sanders *et al.* (2016) and

Santos *et al.* (2018), who highlighted the importance of employee support systems such as improved human-machine interfaces to relieve employees of routine activities and create a motivating work environment.

4.7 Conclusions and future research directions

This chapter carried out a comprehensive literature review regarding the synergic relationship between Industry 4.0 and Lean Management. By exploring the best practices in this discipline, it highlights a set of potential relationships between the two paradigms (see Table 10). In this sense, the findings show that Industry 4.0 technologies have been combined with a variety of Lean tools and practices like JIT, Kanban, SPC, TPM, pull production, kaizen, standard work, and VSM. Indeed, the six real-world examples implemented Industry 4.0 to support existing Lean practices, which confirms previous studies that postulate that research focused on the effect of Industry 4.0 on LM has more contributions than the research area focused in the opposite direction (i.e., Lm as an enabler for Industry 4.0 implementation) (Buer *et al.*, 2018; Pagliosa and Tortorella, 2019; Ciano *et al.*, 2020). More in detail, the results indicate that technologies aimed at increasing data collection (e.g., sensors, QR Code, and RFID) and connectivity (e.g., ERP, CPS and IoT) have strong synergistic relationships with LM practices, even when implemented in different contexts. These technologies are used to identify and eliminate critical sources of waste, such as waiting, extra-processing, defects, and stocks, as well as improve customer satisfaction. In general, in all examples – no matter whether large corporations or SMEs – data and connectivity were a decisive competitive advantage for the companies. Big data analytics technologies were used to monitor and control production, machines, and processes, also proving to have great synergy with LM pratices. Regarding simulation, although some scholars claim that simulation technologies may have lost their novelty and research interest (Pagliosa and Tortorella, 2019), they can be used in different ways by production systems (eg., production scheduling and planning), which increases their capacity to support LM practices.

Therefore, this study contributes to intensifying the debate on Industry 4.0 and Lean Management by highlighting its characteristics and applications in different contexts and identifying the synergies between them. First, the six real-world examples confirm previous studies that suggest the synergic relationship that exists between the two paradigms. Second, the best practices presented make explicit a set of potential relationships and, therefore, provide a more clear understanding of the outcomes of an Industry 4.0-LM integration. Finally, this study highlights the importance of the so called soft practices when implementing Industry 4.0, as different or even contradictory results can be obtained depending on the size, culture, and geography of the company. Hereby, an attractive direction for future research could be to investigate the role of soft Lean practices in facilitating Industry 4.0 implementation, for example in terms of their contribution to create openness, orientation, and to promote autonomy and team working. There is also a need for additional empirical studies that take into account the particular context of SMEs, as they often lack expertise and have fewer resources to invest in new technologies than large corporations (Mittal *et al.*, 2018a; Moeuf *et al.*, 2020). As such, this group of industries certainly deserves more attention. Thus, with more studies exploring best practices in SMEs, they could be more willing to take the first steps to transform their operations through Industry 4.0. This study also contributes to practice as it provides insights into the synergistic relationship of Industry 4.0 and LM in specific contexts, that can be used for managers experiencing similar situations. Furthermore, investigating best practices in the simultaneous implementation of Industry 4.0 technologies and LM practices can give managers a better understanding of the proper tools/practices of both paradigms to cope with high customization requirements, layout problems, bottlenecks, quality control, etc.

This chapter has, however, two main limitations. The first limitation concerns the exploratory character of the research design. Despite exploratory studies being extremely important to deepen the knowledge in new research areas, empirical studies are critical to the improvement and assessment of existing theories, adding credibility. The second limitation is that the initial search of the study was limited to papers published between 2015 and 2018. However, in order to minimize this constraint, more recent and relevant documents were included in the sample for further analysis.

Chapter 5. Conclusions

This chapter presents the synopsis of the thesis, its contributions, and the limitations and future research.

5.1 Synopsis

In recent years, Industry 4.0 has become one of the most popular strategies to help companies deal with complex market requirements such as mass customization. For many firms, the correct implementation of Industry 4.0 seems to be an essential step to remaining competitive in today's business environments. However, the subject is still immature and its requirements and implications are not yet clear to most SMEs and many other firms that are struggling to implement this revolutionary approach.

This thesis was designed to achieve four main aims: (1) to synthesize the existing literature in Industry 4.0 and identify common challenges and opportunities for SMEs in Industry 4.0 implementation; (2) to identify the resources and capabilities required to implement Industry 4.0 in SMEs. Furthermore, based on mainstream theories such as resource-based view (RBV) and dynamic capability theory, it seeks empirical evidence on how SMEs use resources and capabilities to gain sustainable competitive advantage; (3) to shed light on how SMEs acquire and/or develop the Industry 4.0 resources and capabilities; (4) to identify real-world examples of Industry 4.0-LM integration in the extant body of knowledge in order to make explicit the best practices that have been implemented by distinct industrial sectors. To do this, contributions related to Industry 4.0 implementation published in academic journals, government reports and consultancy reports, and other sources were analyzed. Two main research topics within Industry 4.0 implementation (e.g., the implementation of Industry 4.0 in SMEs and its integration with Lean Management approach) were highlighted. Then, the academic and practitioner debate about them was summarized. This led to the conclusion that Industry 4.0 literature is an extensive and heterogeneous subject and, therefore, still characterized by some weaknesses and gaps (eg., Industry 4.o implementation research needs to be further developed). These gaps have been organized into four key questions that suggest some directions for future research. (RQ1) What are the challenges and opportunities for SMEs in the Industry 4.0 field? (RQ2) What are the resources and capabilities for Industry 4.0 implementation in SMEs? (RQ3) How can these resources and capabilities be acquired and/or developed and (RQ4) How to integrate Industry 4.0 and Lean Management? (see Chapter 1).

Answering the research questions, in Chapter 2 (RQ1), 16 common challenges faced by SMEs when implementing Industry 4.0 initiatives were identified and discussed under the scientific literature. Financial resources, investment costs, lack of cost-benefit analysis of relevant technologies, lack of technical knowledge, skills gap, adoption of advanced technologies, top management support, organizational culture, new business models, high complexity, lack of IT infrastructure, legal uncertainty, collaboration strategies, data security issues, lack of uniform standards, and lack of comprehensive strategy of implementation were highlighted as relevant challenges faced by them. While discussing those challenges, suggestions for overcoming them were provided. In this sense, government support of all types (financial and non-financial) was highlighted as having a key role in promoting the development of innovations in SMEs.

Chapter 3 (RQ2 and RQ3), provided a comprehensive list of 33 resources and capabilities from the extant literature that were highlighted because they were considered relevant for the implementation of Industry 4.0 in SMEs. These resources and capabilities have been structured in three different dimensions (i.e., technological, organizational, and external) and validated by analyzing the experiences of five Portuguese SMEs from three different sectors: automotive, automation, and textile. Then, the findings were analyzed through the lenses of the RBV and dynamic capabilities theories. This holistic approach has been used to seek empirical evidence on how SMEs use resources and capabilities to implement Industry 4.0 initiatives and gain sustained competitive advantage. The literature analysis revealed that these issues have been largely overlooked in previous research. In summ, the results showed that, although the examined companies recognize the importance of combining the technological, organizational, and external resources and capabilities to increase value creation and improve industrial performance, not all 33 resources and capabilities previously identified in the literature are being required by them. In fact, the results strongly suggested that all five Portuguese SMEs prioritize resources and capabilities that enable real-time data collection and facilitate connectivity in order to improve decision-making processes, as it will allow for a faster reaction to market changes. Moreover, the results suggested that the Portuguese SMEs are betting on their innovation capabilities. On one hand, they develop the resources and capabilities internally, for example, through R&D, top management commitment, and making use of training capabilities, and on the other hand, when it is not possible to develop them internally, they search for it externally, through hiring skilled employees and establishing innovative collaboration networks.

Finally, in Chapter 4 (RQ4), the real-world examples presented have shown that Industry 4.0 technologies can be combined with a myriad of Lean tools and practices like JIT, Kanban, SPC, TPM, pull production, kaizen, Standard work, and VSM, regardless of the company size. On the other hand, when it comes to Industry 4.0 technologies, the analysis suggested that technologies that promote data collection (e.g., sensors, QR Code, and RFID) and connectivity (e.g., ERP, CPS, and IoT) are preferred, as they have strong synergistic relationships with LM practices, even when implemented in different contexts. It confirms previous studies that have indicated the synergic relationship that exists between these two paradigms (e.g., Buer et al., 2018; Rossini et al., 2019; Ciano et al., 2020).

5.2 Contributions

This section presents the theoretical and practical contributions of the thesis.

5.2.1 Contribution to Theory

This thesis contributes to the Industry 4.0 literature in several ways. First, the existing literature on Industry 4.0 was summarized allowing the identification of thematic and theoretical gaps. This might potentially contribute to intensifying the scientific interest in the Industry 4.0 topic which has not yet been fully presented. Although research in Industry 4.0 has grown over the years, the subject is extremely vast and heterogeneous, so topics such as the implementation of Industry 4.0 in SMEs and its relationship with other management paradigms like Lean Management are still under investigation (e.g., Mittal et al., 2019; Cimini et al., 2020, Ciano et al., 2020).

Second, it contributes to theory as it identifies a set of 16 common challenges faced by SMEs to implement Industry 4.0 and, then, provides suggestions for overcoming these challenges.

Third, this thesis sought to shed light on the resources and capabilities required by SMEs to successfully implement Industry 4.0 and explore how these resources and capabilities can be acquired and/or developed. The findings have been structured in three dimensions (i.e., technological, organizational, and external) and analyzed through the lenses of mainstream theories such as resource-based view (RBV) and dynamic capability theory. This research holds important implications for scholars, who can develop a richer knowledge of the Industry 4.0 implementation in SME debate. Moreover, this is among the first studies to use RBV and dynamic capabilities theories for analyzing the Industry 4.0 resources and capabilities in SMEs.

Forth, this thesis contributes to intensifying the debate on Industry 4.0 and Lean Management by exploring existing systems in which Industry 4.0 technologies and LM practices have been combined. The best practices presented revealed a set of potential relationships, providing a more clear understanding of the outcomes of an Industry 4.0-LM integration. The ultimate goal was to highlight the strong link between these two manufacturing approaches in order to provide new insights into this research area.

Lastly, this thesis also contributes to theory by highlighting the importance of soft Lean practices such as Top Management Commitment, when implementing Industry 4.0. The literature has already stated that soft practices are crucial to create a more appropriate environment for implementing Industry 4.0 and gaining a competitive advantage over existing and potential competitors (Kinzel, 2017; Piccarozzi et al., 2018).

5.2.2 Contribution to Practice

This thesis provides an overview of the Industry 4.0 topic. More specifically, the thesis focuses on how companies can implement Industry 4.0 to get the most benefits from it. This is of particular importance for managers, considering that Industry 4.0 has proven to be an imperative strategy to predict market needs and strengthen competitiveness (S. Wang, *et al.*, 2016; Zheng *et al.*, 2018). A clear understanding of the specific customer requirements may avoid losing customer orientation in an environment as competitive as the new Industry 4.0 reality (Kiel et al., 2017; Müller *et al.*, 2018).

First, this thesis provided a more comprehensive understanding of the potential challenges and risks of implementing Industry 4.0. It can help industrial managers focus on operations that are crucial to their business development and eradicate potential barriers to adopting modern technology. Furthermore, as the study also provided SME-specific solutions to overcome these challenges, it can provide insights for SME managers into the opportunities that arise with this new manufacturing paradigm.

In the empirical part of this thesis, managers recognized the importance of Industry 4.0 in today's business contexts while acknowledging that there is no clear guide or list of resources and capabilities for implementation in SMEs. In this sense, this thesis holds important implications for management practice by shedding light on how SMEs can approach Industry 4.0 in order to maximize its benefits. This can be done through the evaluation of the resources that a firm possesses and that have the potential to generate sustainable competitive advantage and then exploiting those resources more extensively (Barney *et al.* 2012). In addition, the 33 resources and capabilities proposed provide managers further understanding of the relevant technological, organizational, and external resources and capabilities to effectively implement Industry 4.0 in Portuguese SMEs. As such, this thesis may encourage Portuguese policymakers to focus their support on the resources and capabilities that have been highlighted as most relevant in this study. In most cases, government support was highlighted as critical to facilitating the transition to Industry 4.0. Governments can also promote the resources and capabilities that proved less popular within the investigated SMEs, for example: additive manufacturing, CPS, M2M, SRM, VR, and new business models. It seems essential as SMEs are considered the backbone of most European economies (Rauch et al., 2019). Furthermore, the focus on Portugal, allowed providing managerial insights into that particular geographical area.

Also, this thesis provided insights into the synergistic relationship of Industry 4.0 and LM in distinct contexts, that can be used for managers experiencing similar situations. Furthermore, investigating best practices in the simultaneous implementation of Industry 4.0 technologies and LM practices can give managers a better understanding of the proper tools/practices of both paradigms that can be combined to cope with manufacturing challenges such as high customization requirements, layout problems, bottlenecks, quality control, etc.

Furthermore, companies often assume that technology investments will positively impact performance and neglect that the organization needs to adapt to the technology solutions. Thus, this thesis called attention to the importance of the soft Lean practices in facilitating the implementation of Industry 4.0 technologies, for example in terms of their contribution to create openness, orientation, and to promote autonomy and team working. This is important because it could potentially help managers to support their employees and enable the organization capable of adapting to new processes on the journey of digital transformation.

Finally, this thesis contributes to practice as it proposes a framework to support SMEs in the implementation of Industry 4.0 (Figure 6). The proposed 4-step process is intended to act as a general guideline for SMEs to successfully implement Industry 4.0. Accomplishing this is a great start for companies wishing to grasp market opportunities and develop a sustainable competitive advantage. As the external environment is not static, either due to rapid technological changes or high competition; the 4-step process represents an iterative process and should be repeated as many times as necessary. Managers may use the results of this thesis to access steps 1, 2, and 3. Also, it is important to highlight that as the (strategic) management of resources/capabilities (see step 4) is at least as important as their mere ownership and use, every employee shall be involved in the implementation of Industry 4.0 in order to develop a digital culture in the company.

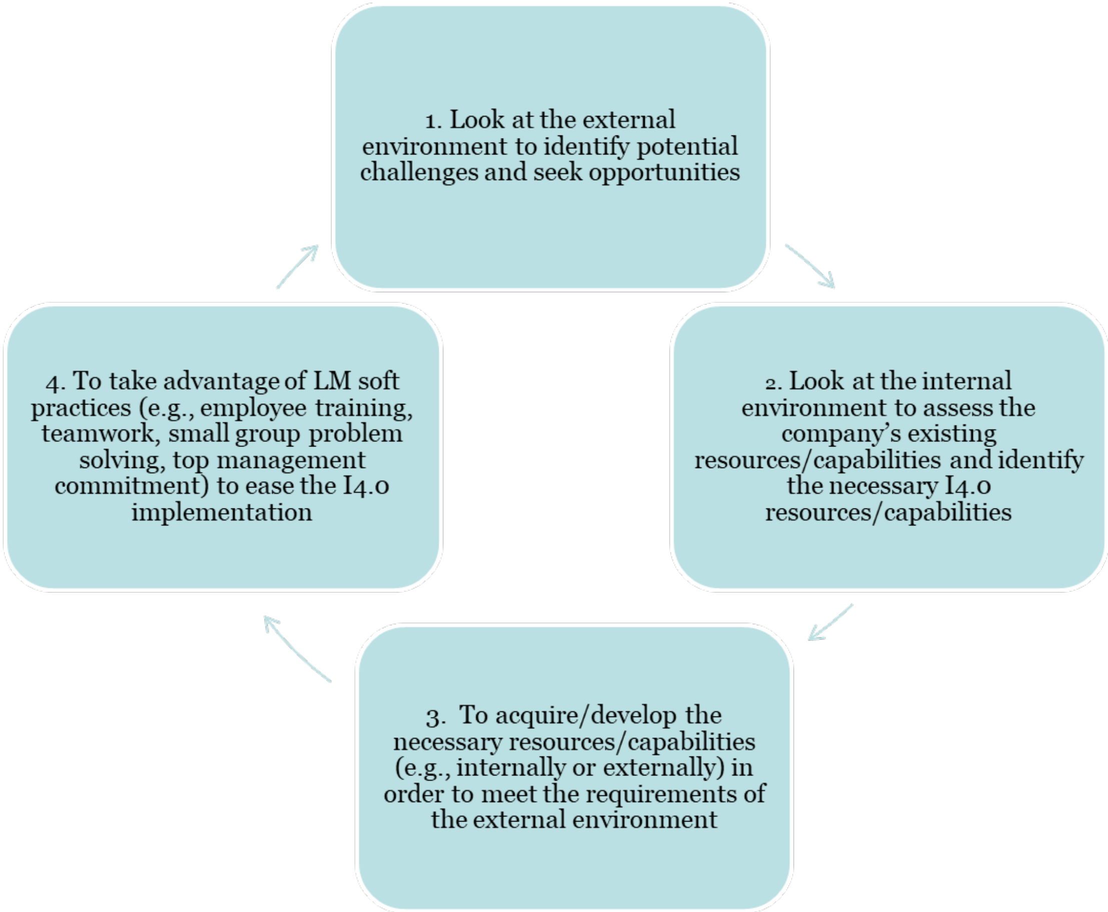

Figure 6. General guidelines for SMEs to start implementing Industry 4.0

5.3 Limitations and Future Research

This thesis is however characterized by some major limitations. First, a semisystematic literature review methodology was employed to investigate the challenges and opportunities within Industry 4.0 (see Chapter 2) and the relationship between Industry 4.0 and Lean Management (See Chapter 4). Although in both chapters the methodology adopted involved the combination of numerous sources of data (e.g., peer-reviewed literature from the largest abstract and citation database (Scopus), conference papers, government reports and consultancy reports), this choice has some weaknesses (e.g., the results are based only on secondary data and have not been empirically tested). The use of primary data directly collected through case studies and questionnaires with industrial managers could increase the reliability of the results. However, a literature review is considered an excellent way for creating new insights and, and make a substantial contribution to the respective area of research (Snyder, 2019).

Second, the empirical part of this thesis (see Chapter 3) focused on SMEs located in Portugal, which may have introduced some sociocultural and political biases to the conclusions, limiting the generalisability of the findings. However, this allows for controlling for several critical factors relating to the diversity of cultural/geographical contexts. As such, two aspects may justify this choice: (1) SMEs represent approximately 99.9% of the Portuguese's companies and (2) The Portuguese Government is strongly promoting digitization to strengthen Portugal's role in the fourth Industrial Revolution.

Third, Chapter 3 considered a sample of five Portuguese SMEs. However, previous studies in the operations management literature such as Mirzaei *et al.* (2021), Dieste *et al.* (2020), and Iakymenko *et al.* (2020) also employed a multiple case study approach using the same number of cases. Moreover, the goal of the thesis was indeed to investigate an emerging topic and highlight a set of findings that might then be empirically tested on a larger and statistically significant sample. Furthermore, despite the sample being composed of companies from three different sectors (automotive, automation, and textile), they have similar strategies to reach markets. This is probably the reason why the research did not find significant differences between the analyzed cases.

Nevertheless, the aforementioned limitations can be considered opportunities for future research.

In Chapter 2, future research could empirically assess the results in SMEs that have different needs and from different contexts. For instance, the results suggested a set of 16 common challenges faced by SMEs; future studies could extend this list to include other challenges that are related to specific conditions of certain SMEs and country contexts.

Regarding Chapter 3, longitudinal case studies or action research methods could be employed to analyze the resources and capabilities required for an effective Industry 4.0 implementation in SMEs. Also, future investigations could verify the possibility of extending these results to other industrial sectors, characterized by more expressive differences regarding their market strategies, and may assess whether the findings are replicable in other countries.

Finally, a further interesting direction for future research concerns the role of soft Lean practices when implementing Industry 4.0, especially in SMEs. Indeed, there is a need for additional empirical studies that focus on the specific context of SMEs, as they often lack expertise and have fewer resources to invest in new technologies than large companies (Mittal *et al.*, 2018a; Moeuf *et al.*, 2020).

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Appendix I: Interview guideline

Section A – Company Profile

A1. General Company Information

- Number of employees:
- Sector:

A2. Information of the Interviewee

- Current position:
- Seniority:
- Specific tasks and areas of responsibility:

Section B – Industry 4.0

B1. Envision Industry 4.0

1) How familiar are you with the term "Industry 4.0"? Can you give a short description about what means Industry 4.0 to you?

2) How do you visualize Industry 4.0?

a) as an evolutionary process of the automation era (3rd Industrial Revolution) just with more digitalization and connectivity or;

b) as 4th Industrial Revolution, with the implementation of disruptive technologies, innovative business models and new customer relationships.

3) Is Industry 4.0 already relevant for your organization?

a) If yes, what is the level of importance of it so far? Could you please make some examples of Industry 4.0 projects that you have implemented or you are going to implement? When did you started and concluded the first Industry 4.0 project?

b) If not, in which timeframe do you see Industry 4.0 as relevant to you? (e.g., short; mid-term; long-term; irrelevant)

4) Is Industry 4.0 relevant for your customers or competitors? Could you please make some examples of Industry 4.0 projects carried out by them?

5) Is your company internally motivated and/or externally pressured towards implementation of Industry 4.0 projects?

6) Which trends or developments, in your opinion, will have a substantial effect on the adoption of Industry 4.0 by SMEs?

B2. Competencies for Industry 4.0 adoption and implementation

7) Which competencies (resources and skills) should be (are) useful/needed to adopt and implement Industry 4.0? Would you like to add other? (see table 8)

8) Did your company have them when you started the first Industry 4.0 project? Do you have them now?

9) Where can these competencies be found or how can they be developed?

10) How can other stakeholders (e.g., government, schools/universities, suppliers/customers) support SMEs in the adoption and implementation of Industry 4.0?

Appendix II – Interview guideline in Portuguese

Seção A - Perfil da Empresa

A1. Informações gerais da empresa

- Número de empregados:
- Setor:

A2. Informações do Entrevistado

- Posição atual:
- Antiguidade:
- Tarefas específicas e áreas de responsabilidade:

Seção B - Indústria 4.0

B1. Visão da Indústria 4.0

1) Quão familiarizado você está com o termo "Indústria 4.0"? Poderia dar uma breve descrição sobre o que significa Indústria 4.0?

2) Como você visualiza a Indústria 4.0?

a) como um processo evolutivo da era da automação (3ª Revolução Industrial), apenas com mais digitalização e conectividade ou;

b) como 4ª Revolução Industrial, com a implementação de tecnologias disruptivas, modelos de negócios inovadores e novos relacionamentos com clientes.

3) A Indústria 4.0 já é relevante para sua organização?

a) Se sim, qual é o nível de importância até agora? Poderia, por favor, dar alguns exemplos de projetos da Indústria 4.0 que a empresa implementou ou ainda pretende implementar? Quando a empresa iniciou e concluiu o primeiro projeto de Indústria 4.0?

b) Se não, em que período você considera que a Indústria 4.0 será relevante para a empresa? (por exemplo, curto; médio prazo; longo prazo; irrelevante)

4) A Indústria 4.0 é relevante para seus clientes ou concorrentes? Você poderia, por favor, dar alguns exemplos de projetos da Indústria 4.0 realizados por eles?

5) Sua empresa é motivada internamente e/ou pressionada externamente para a implementação de projetos da Indústria 4.0?

6) Quais tendências ou desenvolvimentos, na sua opinião, terão um efeito substancial na adoção da Indústria 4.0 pelas pequenas e médias empresas?

B2. Competências para adoção e implementação da Indústria 4.0

7) Quais competências (recursos e habilidades) devem ser (são) úteis/necessárias para adotar e implementar a Indústria 4.0? Gostaria de adicionar outro? (ver tabela 8)

8) Sua empresa já os possuía quando iniciou o primeiro projeto da Indústria 4.0? A empresa os tem agora?

9) Onde essas competências podem ser encontradas ou como podem ser desenvolvidas?

10) Como outras partes interessadas (por exemplo, governo, escolas/universidades, fornecedores/clientes) podem apoiar as PMEs na adoção e implementação da Indústria 4.0?

Appendix III: Transcription of the interviews

Company A (CA)

Section A – Company Profile

A1. General Company Information

- Number of employees: 80
- Sector: automotive

A2. Information of the Interviewee

- Current position: p*roduction maintenance and logistics manager*
- Seniority: *8 years*
- Specific tasks and areas of responsibility: *production supervision and I am also responsible for the maintenance of the factories and the maintenance of the production equipment. We have 3 areas (maintenance, logistics and planning) and in all of these areas there is a person who reports to me.*

Section B – Industry 4.0

B1. Envision Industry 4.0

1) How familiar are you with the term "Industry 4.0"? Can you give a short description about what means Industry 4.0 to you?

CA: *Industry 4.0 is a buzzword, it is the industrial 4th revolution which turns out to be the digitization of all processes, that is, there is no basis on paper and we transform it all into digital ecosystems*

2) How do you visualize Industry 4.0?

a) as an evolutionary process of the automation era (3rd Industrial Revolution) just with more digitalization and connectivity or;

b) as 4th Industrial Revolution, with the implementation of disruptive technologies, innovative business models and new customer relationships.

CA: a*) We see Industry 4.0 as an evolutionary process, it is a consequence of the technological revolution that has been taking place.*

3) Is Industry 4.0 already relevant for your organization?

a) If yes, what is the level of importance of it so far? Could you please make some examples of Industry 4.0 projects that you have implemented or you are going to implement? When did you started and concluded the first Industry 4.0 project?

b) If not, in which timeframe do you see Industry 4.0 as relevant to you? (e.g., short; mid-term; long-term; irrelevant)

CA: *Very important! We have 3 projects so far, we have a project that started in the logistics area (EDI) in 2017. For example, we have transactions with customers in which there is no paper involved, that is, we receive an electronic order, and internally, we transform it into an order. So, the production order, shipping guide, invoice, and everything is done electronically. We are also implementing a maintenance program (started in 2018) in which we will monitor the equipment, e.g., we will know in real-time the energy consumption, temperature, etc. We will use sensors through wireless to allow to control the temperature and energy consumption. This can be applied directly by the equipment of the machine or can be general in the output of the general electric panel. Then, if we want to go more in detail we can apply it to each motor of the machine. We are energy-intensive consumers, so monitoring these data is very important for us. That is, we can have a general output or we can monitor each motor that is consuming more or less energy. Besides monitoring the energy, this system allows predictive maintenance, i.e., to know if there are differences between large amperage or temperature, which could indicate a problem. In this sense, we are discussing predictive maintenance, that is, predicting and anticipating failures. This project is still in the implementation phase. We also want to implement a production program (production control) where we can monitor the production system online from anywhere through a mobile application or a tablet. Thus, we can receive real-time information about what we have already produced, our position regards, our goals, if the orders are already satisfied, etc. The idea for me is to be here in my office and to be aware if a machine is broken, what is being produced, if we has already reached the goal, if the order is already satisfied, that is, to monitor minute by minute to react quickly to any change. Another example, the machines that we have currently installed allow the vendors access through "timeview" and make diagnoses of the machine problems. Today, all the equipment we have in the factory has remote access.*

4) Is Industry 4.0 relevant for your customers or competitors? Could you please make some examples of Industry 4.0 projects carried out by them?

CA: *Of course, we know that they are using Industry 4.0 technologies to control and monitor production. I think is important to adapt ourselves to this evolution because the role, let us say, of providing faster responses and having reliable data and being able to monitor production on a daily bases is clearly important. We have to move towards that. We have few direct competitors because, in some product ranges, we are practically exclusive but we maintain a fair competition. We need to compare ourselves because we have some customers in common and the customer can buy the product from anyone.*

5) Is your company internally motivated and/or externally pressured towards implementation of Industry 4.0 projects?

CA: *Although the company has approximately 8 years of existence, we have grown from 12 million euros to 40 million euros in 2018, that is, we have grown a lot, but we had to take the step to I4.0, no doubt that it is the door to the future and it is the reality now. Especially because there are not enough resources, so if there are new tools, we have to use them to remain competitive. All the implementations that are being implemented here will be implemented later in our factory in Mexico. Here, they were used as a pilot project, but then what has worked and what we have learned from the mistakes we will try to repeat there. Now, for example, we are working on products to be released in the next 4 or 5 years, that is, we are anticipating what the market will require because if we are only thinking about today we will die quickly. Today, taking sustainability issues into account is very important from the market point of view. Then, even more products at the end of their life cycles are being recyclable and we know that currently, some compounds cannot be. Thus, whoever reaches it first it will be able to gain the market. In fact, the end customer is demanding that once they are also being pressured in that direction. Therefore, the environmental aspect is quite important.*

6) Which trends or developments, in your opinion, will have a substantial effect on the adoption of Industry 4.0 by SMEs?

CA: *I think it is a question of monitoring, of knowing the second, the minute of what we have to produce, what comes in, what we have, what we have in stock, and what we sell. Today the manager needs to have this information online to manage. For example, I'm attending a post-graduate degree in operations management and we were talking about it. Before it was the so-called production launchers who were going to collect the data (we are talking about a factory that has 80 machines), then 4 more people were needed to impute the data. So the data was collected on Monday* *and only on Friday, the manager was able to see if there were any breakdowns. Thus, having the information and being able to treat it immediately, and quickly, is arguably the most important thing nowadays. I think we also have to know how to extract information and take advantage of it and make reports to react immediately. Since we are not such a large organization, we do not have these extreme information delays, but even now, sometimes things can happen if we do not have the information coming in at the right time. Another example, we share a cloud system with our plant in Mexico, the cloud computing allows us to monitor and control our plant in Mexico through horizontal integration, as well as providing faster feedback if any problem arise. We also use Lean practices such as top management commitment and 5S.*

B2. Competencies for Industry 4.0 adoption and implementation

7) Which competencies (resources and skills) should be (are) useful/needed to adopt and implement Industry 4.0? Would you like to add other?

CA: *See table 8.* Regarding the new business model, o*ur product has some specificity and has to be validated by the customer. It also depends on the customer the type of equipment that the product must be processed. Therefore, at this moment, e-commerce works more to promote the company and make early contact.*

8) Did your company have them when you started the first Industry 4.0 project? Do you have them now?

CA: *We started slowly and got the resources/capabilities as they were needed.*

9) Where can these competencies be found or how can they be developed?

CA: *We have consulting and training companies (outsourced) that work in partnerships with us.*

10) How can other stakeholders (e.g., government, schools/universities, suppliers/customers) support SMEs in the adoption and implementation of Industry 4.0?

CA: *We make partnerships with universities when it is necessary to develop new products or use their laboratories. Also, we have support from Government. Portugal's Government is providing great incentives to SMEs – Portugal 2020 program – investing in innovation and innovative products with competitive advantage.*

Company B (CB)

Section A – Company Profile

A1. General Company Information

- Number of employees: 46
- Sector: automotive

A2. Information of the Interviewee

- Current position: *R&D and production manager*
- Seniority: *8 years*
- Specific tasks and areas of responsibility: *R&D manager*

Section B – Industry 4.0

B1. Envision Industry 4.0

1) How familiar are you with the term "Industry 4.0"? Can you give a short description about what means Industry 4.0 to you?

CB: *In our case, not as users, but as implementers, Industry 4.0 has changed the paradigm of the solutions we present to our customers. We no longer have standard solutions because customers want solutions seamlessly that wrap around their existing production lines or processes. Industry 4.0 deals mainly with the interaction between systems, which facilitates decision-making by those who manage and who control the plant.*

2) How do you visualize Industry 4.0?

a) as an evolutionary process of the automation era (3rd Industrial Revolution) just with more digitalization and connectivity or;

b) as 4th Industrial Revolution, with the implementation of disruptive technologies, innovative business models and new customer relationships.

CB: a*) For us it is an evolution, the equipment already existed. We started to produce equipment in 2006, when the company was created. The equipment was operated based on microcontroller systems, that is, autonomous systems that allowed the development of a given task and at the moment our equipment is based on computers.*

3) Is Industry 4.0 already relevant for your organization?

a) If yes, what is the level of importance of it so far? Could you please make some examples of Industry 4.0 projects that you have implemented or you are going to implement? When did you started and concluded the first Industry 4.0 project?

b) If not, in which timeframe do you see Industry 4.0 as relevant to you? (e.g., short; mid-term; long-term; irrelevant)

CB: *It is increasingly important, as the decision centers want to have control, that is, the ability to analyze what is happening in real-time or in the integration of the equipment in a production line or in a process. So we see this paradigm as extremely important and a very useful way to meet market needs. In the middle of 2014 we started to think about Industry 4.0 and in 2015 we implement our first project. After the implementation of our first Industry 4.0 project (employment of sensors and RFID technologies), through a smartphone app we were informed almost instantaneously that the machine 'A' failed this morning and this will result in a downtime at 4pm on the x-line equipment. This allowed us to make better decisions to react to these unpredictable events. If I know that there has been a failure and that this machine is going to stop, I can streamline the process and manage all processes in the best way to ensure productivity. Also in terms of quality, if we have systems that can interact with other systems, we can do better traceability. Thus, if a certain component passed through a machine, this component has already been identified, and it is not necessary for the operator to do so. Anyway, all these factors will influence time, if we produce better, with more quality at first, we will also reduce time and costs.*

4) Is Industry 4.0 relevant for your customers or competitors? Could you please make some examples of Industry 4.0 projects carried out by them?

CB: *We do not have competitors in Portugal, our competitors are very large companies. As we are an SME, we differentiate ourselves from large companies by having the ability to customize and adapt our products to the customer's needs. We have this flexibility that multinationals do not have. We do not know about their Industry 4.o projects.*

5) Is your company internally motivated and/or externally pressured towards implementation of Industry 4.0 projects?

CB: *Our motivation is daily, we always try to improve and we do not need this external pressure, although it is healthy for us. We see what they our competitors are doing and what we can do better.*

6) Which trends or developments, in your opinion, will have a substantial effect on the adoption of Industry 4.0 by SMEs?

CB: *For me, providing training to employees and seeking solutions in the market is the best way to integrate ourselves into this evolution. It is very important to invest in workers. It was the time that workers were like machines only performing repeated tasks. But this has changed, and we must take advantage of their potential in developing ideas and solutions. In our case we perform an annual assessment at the company in order to identify our training needs, and what we would like to learn and improve and then this is approved by our human resources department. We also can request specific training if we feel that is needed. We also use top management commitment and other Lean practices to make the employees more engaged and improve their digital culture.*

B2. Competencies for Industry 4.0 adoption and implementation

7) Which competencies (resources and skills) should be (are) useful/needed to adopt and implement Industry 4.0? Would you like to add other?

CB: *See table 8.* We *started implementing mechanisms inherent to "Industry 4.0" in mid-2014, and, in the future, we also intend to include and improve these mechanisms so that decision-making can be done virtually instantly and without human intervention for continuous monitoring of the machines. The machines can be associated with different types of sensors and also with actuators that allow the virtualization of the supervisory systems, thus remotely monitoring processes.*

8) Did your company have them when you started the first Industry 4.0 project? Do you have them now?

CB: *We have them now.*

9) Where can these competencies be found or how can they be developed?

CB: *Most of our skills are acquired by studying, researching and betting on ourselves, in our training, since we want to keep up to date with the evolution of things. In addition, there are many ways to get this information and technologies, either through our own suppliers who provide solutions according to our real needs or in-house through our R&D department which assists us in the development of innovative solutions.*

10) How can other stakeholders (e.g., government, schools/universities, suppliers/customers) support SMEs in the adoption and implementation of Industry 4.0?

CB: *In every year, we work with trainees from Universities and Vocational Schools which is a way to integrate and share knowledge.*

Company C (CC)

Section A – Company Profile

A1. General Company Information

- Number of employees: 240
- Sector: automotive

A2. Information of the Interviewee

- Current position: *continuous improvement and human resources manager*
- Seniority: 22 *years*
- Specific tasks and areas of responsibility: production process manager

Section B – Industry 4.0

B1. Envision Industry 4.0

1) How familiar are you with the term "Industry 4.0"? Can you give a short description about what means Industry 4.0 to you?

CC: For me *is a way that the equipment has to communicate, so the equipment can be connected online and give all the information regarding the processes, quality, etc. At any moment we can obtain information on the produced pieces. In addition, it allows comparing the product with a standard model, with the targets, as well extract the key performance indicators.*

2) How do you visualize Industry 4.0?

a) as an evolutionary process of the automation era (3rd Industrial Revolution) just with more digitalization and connectivity or;

b) as 4th Industrial Revolution, with the implementation of disruptive technologies, innovative business models and new customer relationships.

CC: *a) I will not say that it is a revolution, but rather an evolution, a continuation of the 3rd revolution, because it is based on all the software that already exists that* *allows doing a data consolidation to provide us real-time information about production processes.*

3) Is Industry 4.0 already relevant for your organization?

a) If yes, what is the level of importance of it so far? Could you please make some examples of Industry 4.0 projects that you have implemented or you are going to implement? When did you started and concluded the first Industry 4.0 project?

b) If not, in which timeframe do you see Industry 4.0 as relevant to you? (e.g., short; mid-term; long-term; irrelevant)

CC*: Yes, it is very important. We started last year (2017) to implement in a pilot area. The information collected on the shop floor is disseminated to several people in the hierarchy and in a format appropriate to each hierarchy. Thus, through a simple mobile (app) the production director can quickly go into the detailed information. The factory director can receive more macro information and the CEO may be in China or in another country and can quickly see what is happening inside the units. Although the company is a Portuguese group, it is present in 16 countries, so many of the decisions are taken by the group so as not to conflict with the decisions of each unit. The company in Portugal will be a pilot in Industry 4.0 for the rest of the group.*

4) Is Industry 4.0 relevant for your customers or competitors? Could you please make some examples of Industry 4.0 projects carried out by them?

CC: *We have competitors, but I do not know to answer.*

5) Is your company internally motivated and/or externally pressured towards implementation of Industry 4.0 projects?

CC: *Internally and externally, yes, we feel the pressure, because we know that this is something that will bring us many benefits in terms of decision-making. Better, more sustained and faster decisions, that are already clear to us.*

6) Which trends or developments, in your opinion, will have a substantial effect on the adoption of Industry 4.0 by SMEs?

CC: *For me, it is the decision-making, it has to be quick and it is something that we often do not have. For example, a question has been made for our production supervisor this morning and he said he still did not have access to the reports. So, things happen, the shift ends and then only after a few hours the data will be entered into the system. Thus, often, only past 3 or 4h we can analyze what happened on a whole shift and this is really a problem. Thereby, the biggest benefits of Industry 4.0 are* *undoubtedly the possibility of rapid decision-making, which may be taken at any moment or even in the middle of a shift. Thus, we may know exactly where we stand, what is already done, what we lose, etc. And that decision may be regarding a specific machine or even a strategic decision by the management.*

B2. Competencies for Industry 4.0 adoption and implementation

7) Which competencies (resources and skills) should be (are) useful/needed to adopt and implement Industry 4.0? Would you like to add other?

CC: *See table 8. No, I think they are all there.*

8) Did your company have them when you started the first Industry 4.0 project? Do you have them now?

CC: *yes, we have.*

9) Where can these competencies be found or how can they be developed?

CC: *We consult partner companies. Nowadays it is very difficult to find skilled employees in this field, so we rely on partner companies to get the know-how and skills we need. We also use lean tools such as kaizen, leadership and 5 min meeting to engage our employees and support them in developing their digital skills.*

10) How can other stakeholders (e.g., government, schools/universities, suppliers/customers) support SMEs in the adoption and implementation of Industry 4.0?

CC: *We have partnerships with universities, but in the Industry 4.0 project, a company is giving us support. Last year we consulted 3 companies that showed us Industry 4.0 models. We are not aware of the government incentives.*

Company D (CD)

Section A – Company Profile

A1. General Company Information

- Number of employees: 57
- Sector: automation

A2. Information of the Interviewee

- Current position: *marketing manager*
- Seniority: 8 *years*

- Specific tasks and areas of responsibility: *responsible for the marketing area of the company*

Section B – Industry 4.0

B1. Envision Industry 4.0

1) How familiar are you with the term "Industry 4.0"? Can you give a short description about what means Industry 4.0 to you?

CD: *Industry 4.0 brings all the advantages because it allows us to have a faster reading of what is happening, thus making decisions faster and more effective.*

2) How do you visualize Industry 4.0?

a) as an evolutionary process of the automation era (3rd Industrial Revolution) just with more digitalization and connectivity or;

b) as 4th Industrial Revolution, with the implementation of disruptive technologies, innovative business models and new customer relationships.

CD: *a) It's an evolution. We have been developing automation equipment, systems and solutions for over 40 years and what we see now is just an evolution of what we had 40 years ago.*

3) Is Industry 4.0 already relevant for your organization?

a) If yes, what is the level of importance of it so far? Could you please make some examples of Industry 4.0 projects that you have implemented or you are going to implement? When did you started and concluded the first Industry 4.0 project?

b) If not, in which timeframe do you see Industry 4.0 as relevant to you? (e.g., short; mid-term; long-term; irrelevant)

CD*: Yes, we have two departments that constitute two business areas, which, although distinct, are part of the company's core activity, allowing research and development processes for automation solutions and new products. So, besides, making use of Industry 4.0 in our factory, we also provide customized Industry 4.0 solutions for our customers. We do not make standardized products and solutions. Our customer is involved in all processes. For example, we have the development, design part, and the engineering part and the client is always working in parallel with us. We don't move forward without customer approval. In addition to developing, designing and implementing integrated automation solutions, we provide an integrated after-sales service for the products sold. For example, if a customer has* *a problem with their equipment, we can remotely fix the damage without the need of going to the place where it happened.*

4) Is Industry 4.0 relevant for your customers or competitors? Could you please make some examples of Industry 4.0 projects carried out by them?

CD: *Our focus is the external market. We know that Industry 4.0 is as important to them as it is to us. Thus, we seek to respond and satisfy the needs of our customers by investing in innovation, quality and continuous training of our human resources to guarantee a consolidated position in the market.*

5) Is your company internally motivated and/or externally pressured towards implementation of Industry 4.0 projects?

CD: *yes, of course! We have to exceed our customer's needs and for this, we invest in R&D to bring industry 4.0 innovative solutions to their problems.*

6) Which trends or developments, in your opinion, will have a substantial effect on the adoption of Industry 4.0 by SMEs?

CD: *For me, it's real-time production tracking. Most of our customers are looking for solutions that allow collecting real-time data for better and more rapid decision-making. They want to know everything that is happening in their factories so they can predict future problems. Also, Kaizen practices and Lean, in general, allow the company to better enter Industry 4.0 by preparing all the ground so that this reading can be done in real-time.*

B2. Competencies for Industry 4.0 adoption and implementation

7) Which competencies (resources and skills) should be (are) useful/needed to adopt and implement Industry 4.0? Would you like to add other?

CD: *See table 8.*

8) Did your company have them when you started the first Industry 4.0 project? Do you have them now?

CD: *yes, we have them.*

9) Where can these competencies be found or how can they be developed?

CD: *As I said before, we have two departments that focus on R&D to develop innovative Industry 4.0 solutions. Also, as skilled workforce is an important asset to remain competitive and due to the shortage of this type of human resources in Portugal, we have become a training entity. We establish an annual training* *calendar, also guaranteeing personalized training tailored to the needs of our customers and other companies.*

10) How can other stakeholders (e.g., government, schools/universities, suppliers/customers) support SMEs in the adoption and implementation of Industry 4.0?

CD: *We are receiving support from the Portuguese government (Portugal 2020 program). We also make partnerships with supplies and customers to develop new products*

Company E (CE)

Section A – Company Profile

A1. General Company Information

- Number of employees: 180
- Sector: textile

A2. Information of the Interviewee

- Current position: *responsible for the maintenance sector and information technologies*
- Seniority: 12 *years*
- Specific tasks and areas of responsibility: *maintenance, automation, IT, software*

Section B – Industry 4.0

B1. Envision Industry 4.0

1) How familiar are you with the term "Industry 4.0"? Can you give a short description about what means Industry 4.0 to you?

CE: *I think that i4.0 is mainly real-time information, it is knowing everything that is happening at that moment and it also involves traceability, that is, it is knowing which product left the company, which was the raw material and all the stages through which ones passed, on which machines, etc.*

2) How do you visualize Industry 4.0?

a) as an evolutionary process of the automation era (3rd Industrial Revolution) just with more digitalization and connectivity or;

b) as 4th Industrial Revolution, with the implementation of disruptive technologies, innovative business models and new customer relationships.

CE: *a) and b) For me, it's a mix of the two. It is certainly an evolution, but at the same time, it is a revolution because we have access to things that did not exist a while ago. No need to go many years ago, things have evolved very fast and we are increasingly dependent on these technologies.*

3) Is Industry 4.0 already relevant for your organization?

a) If yes, what is the level of importance of it so far? Could you please make some examples of Industry 4.0 projects that you have implemented or you are going to implement? When did you started and concluded the first Industry 4.0 project?

b) If not, in which timeframe do you see Industry 4.0 as relevant to you? (e.g., short; mid-term; long-term; irrelevant)

CE*: Yes, very important. For example, another thing that has changed is the ease of transport, for example, for our industry it doesn't matter where the customer is located, as we are able to reach them, at least within Europe. So, for us, it doesn't matter much if we are here, in Spain, or in Germany. Our customer does not have to know where our factory is located but only needs to know about orders, product quality, etc. We export more than 90% of production. Our idea is to constantly be evolving. The first big change in the company was in 1999 when it had old facilities and we decided to build a completely new building where we kept only the employees and very few machines, just the most recent ones. Therefore, in recent years the company has always invested in new machines, software developments and acquisitions. Nowadays, the technology we have is what currently exists on the market. In 2005 we made a change in the dyeing section and now it is fully automated, for example, the operator only presses the on and off buttons, and everything else is done automatically, such as the selection of products to be dyed, temperature level, etc. So, the information is displayed on a computer and we can know which machines are working and what they are doing, which part of the process they are in, how much time is left and everything that will come next. We already have software that optimizes and plan the processes for each machine. We are now looking into purchasing weaving software that brings the looms online. We are prospecting to see what is on the market and we intend to have this implemented for the next year. With this, when a customer orders, for example, x meters of fabric, we can predict the delivery time. We are expecting to implement this in 2019.*

4) Is Industry 4.0 relevant for your customers or competitors? Could you please make some examples of Industry 4.0 projects carried out by them?

CE: *For our competitors, I think so. For the customers, we are working for the next year on the development of production management software, so the customer will have access to the status of his order. For our competitors, I think so. For the customers, we are working for the next year on the development of production management software, so the customer will have access to the status of his order.*

5) Is your company internally motivated and/or externally pressured towards implementation of Industry 4.0 projects?

CE: *The pressure for improvements has to exist and market demands drive the company's evolution. If a company stagnates and does not invest in machines and technologies, it quickly becomes obsolete and ceases to be competitive.*

6) Which trends or developments, in your opinion, will have a substantial effect on the adoption of Industry 4.0 by SMEs?

CE: *Real-time information. Now I want to know everything that's going on at the company and I don't need to be here. I can be anywhere in the world and having a computer or mobile phone with internet, I can keep up with everything. Moreover, at the moment, we have a high turnover of workers. Due to the difficulties we are facing, Lean practices such as top management commitment, team working, and kaizen help us in the implementation of our I4.0 projects. We need to invest in people. Every day we are faced with problems precisely at the level of the soft skills of our employees. Most of our employees are not young, so they have more difficulty accepting changes in their work environment than the youngest. We need to help them develop a digital culture.*

B2. Competencies for Industry 4.0 adoption and implementation

7) Which competencies (resources and skills) should be (are) useful/needed to adopt and implement Industry 4.0? Would you like to add other?

CE: *See table 8. Regarding RFID or QR we have been trying to adopt it for a few years. For example, when the piece comes out of the loom, each piece has a serial number. It would be easier if it had something written on the fabric. The problem is that when the fabric advances in the line the process can be violent and destructive for the labels, be it RFID or even QR codes. We have already tried partnerships with companies to develop something that solves that problem, but it has not been possible yet. Concerning cloud computing, we bought an external cloud server two years ago. However, we are still not convinced if it was a good idea, not because of security, or because we are at risk by having a server inside or outside of the factory, but because* *we no longer have control of our data. So, if any problem occurs, we depend on third parties.*

8) Did your company have them when you started the first Industry 4.0 project? Do you have them now?

CE: *Yes*

9) Where can these competencies be found or how can they be developed?

CE: *For example, in the case of dyeing, employees were used to working with fully manual machines. When we moved to the new plant, where some tasks were automated, they showed some reluctance, but they got adapted over time, thanks to strong management commitment and training programs. We also bet on developing new products and sometimes we launch new things on the market. For example, we have already had exclusivity in one type of product for almost 3 years. We develop technologies internally in our R&D department and, when necessary, we seek partnerships with suppliers. Moreover, because many of the industry needs arise from very specific processes, we use our know-how to provide customers with customized solutions.*

10) How can other stakeholders (e.g., government, schools/universities, suppliers/customers) support SMEs in the adoption and implementation of Industry 4.0?

CE: *We are always in partnership with universities in the development of new products and we also receive support from government programs. We have already won the National Innovation Award.*