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The role of organizational factors in the adoption of Smart Manufacturing

A study in the automotive industry

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ABSTRACT

Smart Manufacturing (SM) lies at the core of Industry 4.0 and envisions the widespread application of advanced technologies within firms' production systems. Since many firms struggle to progress in SM, Operations Management literature has recognized the importance of investigating determinants of firms' SM advancement. However, empirical investigations in this field have been largely characterised by a technology-based approach, while the potential role of non-technological determinants is still to be fully unveiled.

Research presented in this doctoral dissertation contributes to closing this gap by investigating how organizational factors contribute to the adoption of SM. In particular, each of the four chapters included in this dissertation can be regarded as a developmental step in the doctoral research. The starting point is an empirical study that, building on evidence from two polar cases in respect to their stage of SM adoption, explores which technological, organizational and environmental factors influence the adoption process. Results of this study point to the importance of absorbing externally generated SM knowledge. Therefore, as a second step, SM adoption is analysed under the theoretical lens of absorptive capacity and technological and organizational factors enabling absorption of SM knowledge are investigated based on four in-depth case studies. This analysis offers evidence of a close association between firms' degree of absorptive capacity and the stage of SM adoption and suggests that the development of absorptive capacity is mainly driven by organizational factors. As a result, twelve case studies are used to shed light on how absorptive capacity allows firms to advance in SM and to explore how organizational factors support the capacity to absorb SM-related knowledge at different stages of SM adoption. Findings from this study suggest research opportunities in the exploration of the role that organizational factors play in the relation between manufacturing strategies and SM. Therefore, as a last step in the doctoral research, Operations Strategy literature is leveraged to develop a theoretical model linking competitive priorities, organizational factors and SM advancement. Survey data from 234 firms are used to test the model.

This doctoral dissertation responds to calls for expanding empirical research on SM and contributes to Operations Management literature on the adoption of SM technologies by enriching the body of knowledge on non-technological determinants of SM and on the relevance of dynamic capabilities for SM. Results also provide evidence-grounded recommendations to firms engaged in the digital transformation on organizational factors that need to be deployed to progress in SM.

Keywords: Industry 4.0, Smart Manufacturing, absorptive capacity, competitive priorities, organizational micro-foundations, multiple case study, survey.

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CHAPTER 1. Introduction

1.1 Investigating the role of organizational factors in the adoption of Smart Manufacturing

Over the last ten years increasing attention has been placed on the emergence of a fourth industrial revolution, also named Industry 4.0 (Kagermann et al., 2013). Industry 4.0 is based on the widespread use of technologies related to digitalization, automation and connectivity in manufacturing contexts (Brettel et al., 2014) and ensures an unprecedented integration between physical objects and digital technologies (Moeuf et al., 2018).

Within the broad Industry 4.0 paradigm, the use of advanced technologies within firms' production systems is commonly referred to as Smart Manufacturing (Frank et al., 2019). Smart Manufacturing (SM henceforth) enables operations that can be controlled and optimized in real time (Moeuf et al., 2018) and promises improvements in firms' operational performance (Delic and Eyers, 2020; Lorenz et al., 2020; Tortorella et al., 2019). In this respect, it is considered strategic to support manufacturing industries, such as the automotive, that are facing a period of market turbulence and rapid technological change (Dalenogare et al., 2018).

Academia has directed considerable efforts towards the investigation of the SM paradigm, as proven by the exponential growth in the number of related publications (Meindl et al., 2021). When, three years ago, my doctoral studies begun, research on SM in the field of Operations Management followed three main strands. Back then, one first challenge for researchers consisted in the definition of the contours of SM, which entailed the identification of its key enabling technologies and of its peculiarities in respect to previous technological shifts (Culot et al., 2020; Frank et al., 2019; Liao et al., 2017). A second research stream aimed at investigating potential applications for SM technologies and resulting benefits (Alexopoulos et al., 2016; Chen et al., 2015; Hofmann and Rüsch, 2017). The analysis of enablers of firms' SM adoption and progression constituted a third avenue of research (Kiel et al., 2017; Mittal et al., 2018; Veile et al., 2019). Efforts in this direction were motivated by the urgency to understand the determinants of fragmented advancement in SM along supply chains and industries (Mouef et al., 2020; Lin et al., 2018).

Following an initial analysis of literature, it seemed clear that this latter research stream was still emergent and hold significant research opportunities, as studies followed a purely technology-driven approach and were typically characterised by a lack of theoretical underpinnings (Kamble et al., 2018). Therefore, the investigation of determinants of SM adoption and progression appeared to be a promising research topic to develop in the frame of my doctoral studies. At the time, conceptual papers were prevalent in light of the novelty of the topic and of the limited adoption by companies (Culot et al., 2020) and researchers were encouraged to engage in empirical analysis and large-scale data analysis (Koh et al., 2019). For this reason, I decided to embrace an empirical approach in my research. The automotive industry was chosen as setting for the analyses in light of the especially fragmented adoption of SM technologies (Lin et al., 2018).

My doctoral journey began with a qualitative case-study research that, building on the technology-organization-environment framework (Tornatsky and Fleischer, 1990), aimed at identifying key factors impacting on firms' ability to advance in SM. To this end, evidence from two automotive suppliers, constituting polar cases in respect to their stage of SM adoption, was used. After this initial investigation, the development of my doctoral research reflects a progressive coming into focus of a narrow set of relevant factors and of a suitable theoretical lens for the analysis. In fact, these initial observations suggested that organizational factors play a major role in the process of SM adoption and that SM advancement critically requires traditional manufacturers to search and incorporate externally generated technological know-how. In this respect, absorptive capacity, i.e. a dynamic capability (Teece, 2007) underpinning firms' ability to acquire, assimilate, transform and exploit external knowledge (Zahra and George, 2002) appeared to be an appropriate theoretical lens. Therefore, a second case-study research was undertaken using data from four automotive suppliers to investigate how absorptive capacity relates to firms' stage of SM adoption and to explore which technological and organizational factors support firm’s ability to absorb external SM knowledge. This analysis revealed a close association between firms' level of AC and the stage of SM adoption and highlighted that the development of absorptive capacity for SM crucially hinges on organizational factors.

Based on results from this study and in light of calls that were simultaneously issued to encourage research on non-technological enablers of SM (Horváth, and Szabó, 2019), the next logical step was to explore in greater depth how organizational factors support knowledge absorption at different stages of SM adoption. The focus was placed on a specific set of organizational factors, namely managerial factors, since the capacity of managers to create, extend, or modify the knowledge base of an organization is a crucial antecedents of firms' absorptive capacity (Jansen et al., 2005). In parallel, the number of case firms was expanded to include a total of twelve automotive suppliers exhibiting different stages of SM adoption. Results of the analyses highlighted that progression in SM is enabled by a co-evolution of firms' absorptive capacity, which is supported by a gradual transformation of managerial factors in place. Case findings also showed that SM advancement spurred from a focus on a broad set of strategic goals and suggested research opportunities in the exploration of manufacturing strategies and SM.

The existence of a close relation between strategy and technology constitutes one of the tenets of Operations Strategy literature, which, in particular, claims that firms' choices concerning technology stem from business strategy (Rosenzweig and Easton, 2010) and that an alignment needs to exist between strategy, technology and the organization in order for performance to accrue (Leong, et al., 1990). However, limited empirical analyses had been performed to explore the form that the generic concept of "alignment" takes (Wiengarten et al., 2013) and none had been undertaken in the context of SM, despite its relevance for both theory and practice. In this respect, investigating the relation between strategy, organizational factors and SM advancement appeared as an original and interesting extension of my studies. Therefore, following a quantitative research approach, a survey was conducted among firms operating in the automotive component industry. Data from 234 SM adopters were used to test a conceptual model linking competitive priorities, organizational micro-foundations oriented to the development of digital dynamic capabilities (Felin et al., 2012; Warner and Waeger, 2019) and SM advancement. This study shed light on the strategic drivers of SM advancement and elucidated the mechanisms through which the organization influences the strategy-SM link.

To summarize, my doctoral research has aimed at going beyond the mere technology-based approach that characterized early studies on enablers of SM. In particular, by combining empirical qualitative and quantitative research methods, my research sought to provide a comprehensive investigation of the role that organizational factors play in determining SM adoption and progression. In what follows, research questions that guided the analyses are presented, the structure of the dissertation is introduced and its main contributions are outlined.

1.2 Aims of the research

In line with the development of academic debate in the field of SM and progressively building on the results of my studies as outlined in Section 1.1, research conducted during my doctoral studies has pursued three main objectives.

1st objective - To investigate technological, organizational, environmental factors enabling SM

Despite the strategic importance of SM, many firms - especially smaller ones - fail to advance in SM (Raj et al., 2020). Since fragmented adoption has the potential to jeopardize benefits tied to SM, investigation of factors determining successful implementation of SM has been recognized as important and timely (Benitez et al., 2020). Under this premise, a case-study research was performed to investigate key factors influencing small and medium enterprises' ability to adopt SM. In particular, two firms that constitute polar cases in respect to their stage of SM adoption were examined to explore the following research question:

RQ1: Which are the key technological, organizational, environmental factors to progress in Smart Manufacturing?

2nd objective - To explore how organizational factors support the development of absorptive capacity in the context of SM

To exploit the potential offered by SM, firms must possess the capacity to search and process new, specialist and fast-evolving SM technological knowledge generated outside their boundaries (Culot et al., 2020; Ricci et al., 2021), and to integrate it with internal knowledge. In this respect, absorptive capacity (Zahra and George, 2002) is expected to be a crucial dynamic capability that firms need to develop to progress in SM. However, few studies have investigated how absorptive capacity evolves to enable more advanced SM stages and how firms' are called to support the capacity to absorb SM-related knowledge at different stages of SM adoption. To fill this gap, multiple case-studies of firms operating as part of the upstream automotive supply chain were used to investigate the following research questions:

RQ2a: How does the stage of Smart Manufacturing adoption relate to the firm's ability to absorb external technological knowledge?;

RQ2b: Which are the technological and organizational factors that drive absorptive capacity in the context of Smart Manufacturing?;

RQ2c: How does absorptive capacity allow firms to progress to more advanced stages of Smart Manufacturing?;

RQ2d: How do managerial factors support knowledge absorption at different stages of Smart Manufacturing?

3rd objective - To investigate the role played by organizational factors in the relation between competitive priorities and SM advancement

According to Operations Strategy literature, firms' decisions concerning technology adoption are guided by business strategy (Rosenzweig and Easton, 2010). In particular, a relation is expected to hold between technological decisions and competitive priorities, i.e., the dimensions of competitive advantage that the manufacturer intends to pursue (quality, delivery, flexibility, and cost) to realize its strategy (Boyer and Lewis, 2002). Although investigating the influence that strategy has on SM-related technological choices may shed light on why SM advancement differs across firms and industries, there is still a lack of understanding of how SM is informed by firms' competitive priorities. Additionally, Operations Strategy recognizes the importance of aligning strategy not only with the technological structure but also with the organization (Anderson et al., 1989). However, there is limited empirical analysis exploring the form that the concept of "alignment" among strategy, technology and organization takes in the SM context. This analysis is valuable to shed light on the mechanisms through which the organization influences the strategy-SM link, thus providing practical guidance to manufacturing executives who are engaged in the SM transformation. With the goal to address these research gaps, survey data from 234 firms operating in the automotive component industry are used to test a model linking competitive priorities, SM advancement and organizational factors, in the form of organizational micro-foundations oriented to SM. This analysis aims at answering the two following research questions:

R3a: What is the relation between competitive priorities and Smart Manufacturing advancement?;

R3b: What is the role organizational micro-foundations oriented to Smart Manufacturing play in the relation between competitive priorities and Smart Manufacturing advancement?

1.3 Structure of the dissertation

This doctoral dissertation consists of four chapter adapted from studies that have already been published in or submitted to international journals, or have been accepted for publications in peer reviewed books. All studies were developed by myself as first author and co-authored with Prof. Alessandro Ancarani, Prof. Carmela Di Mauro and Prof. Florian Schupp.

The chapters of this dissertation reflect the research objectives detailed in Section 1.2. In particular, **Chapter 2**, based on *"Where the rubber meets the road. Industry 4.0 among SMEs in the automotive sector"*[1], builds on the technology-organization-environment framework (Tornatsky and Fleischer, 1990) and uses evidence from two polar cases to investigate key factors for successful adoption of SM technologies. **Chapter 3**, adapted from *"Stairway to heaven: how firms build absorptive capacity to succeed in Smart Manufacturing"* [2] *,* is based on the analysis of four in-depth case studies and aims at linking firms' level of absorptive capacity relates to the stage of SM adoption at shedding light on technological and organizational factors that enable absorptive capacity in the SM context. **Chapter 4** builds on case study evidence from twelve firms to investigate how how absorptive capacity allows firms to advance in SM and to explore how

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[1] Arcidiacono, F., Ancarani A., Di Mauro C., Schupp, F., 2019. Where the rubber meets the road. Industry 4.0 among SMEs in the automotive sector. IEEE Engineering Management 47(4): 86-93.

[2] Arcidiacono F., Ancarani A., Di Mauro C., Schupp F., forthcoming. Stairway to heaven: how firms build absorptive capacity to succeed in Smart Manufacturing. In Florian Schupp, Heiko Wöhner (eds.), Digitalisierung im Einkauf. 2nd ed. Wiesbaden: Springer Gabler.

managerial factors support the capacity to absorb SM-related knowledge at different stages of SM adoption. This chapter is based on *"The role of absorptive capacity in the adoption of Smart Manufacturing"*[3]. **Chapter 5**, adapted from *"Linking competitive priorities, SM advancement and organizational micro-foundations"*[4], uses data from 234 SM adopters to quantitatively investigate the role that organizational micro-foundations play in the relation between strategy and SM advancement. Figure 1 provides an overview of the studies included in the dissertation and highlights the relationship among them.

Finally, **Chapter 6** concludes the dissertation by presenting the contributions of my doctoral research to both theory and practice, as well as discussing limitations and future research directions.

1.4 Contributions

The studies included in this dissertation respond to calls in Operations Management literature for expanding empirical SM research (Koh et al., 2019; Culot et al., 2020) and contribute to research on determinants of SM advancement (Benitez, Ayala, and Frank 2020; Horváth and Szabó, 2019; Lorenz et al., 2020; Moeuf et al., 2020) by shedding light on the influence that organizational factors play in enabling SM adoption and progression. Each chapter delivers specific contributions to the debate. In particular, **Chapter 2** highlights that organizational factors, more than technological and environmental ones, are at the root of firms' different ability to progress in SM and that SM requires firms to rely on externally generated technological knowledge**. Chapter 3** contextualizes the general theory of absorptive capacity to the SM context and introduces a conceptual framework that identifies which organizational factors are relevant for absorbing SM knowledge. Building on these results, **Chapter 4** enriches the body of evidence on the relevance of dynamic capabilities for SM by providing an analysis of how absorptive capacity evolves to enable more advanced SM stages and by shedding light on how managerial factors need to evolve to support knowledge absorption and different stages of SM. Finally, **Chapter 5** extends research on determinants of SM advancement by shedding light on the influence of competitive priorities and organizational micro-foundations.

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[3] Arcidiacono, F., Ancarani A., Di Mauro C., Schupp F., 2022. The role of absorptive capacity in the adoption of Smart Manufacturing. International Journal of Operations & Production Management 42(6): 773-796.

[4] Arcidiacono F., Ancarani A., Di Mauro C., Schupp F. Linking competitive priorities, SM advancement and organizational micro-foundations. (Submitted to the International Journal of Operations & Production Management).

	Chapter 2 Investigating technological, organizational and environmental factors enabling Smart Manufacturing (SM)	**Chapter 3** Linking absoprtive capacity and Smart Manufacturing	**Chapter 4** Building absorptive capacity to progress in Smart Manufacturing	**Chapter 5** The role of organizational micro-foundations in the relation between competitive priorities and Smart Manufacturing advancement
Research questions	**Objective 1** *RQ1 - Which are the key technological, organizational, environmental factors to progress in Smart Manufacturing?*	**Objective 2** *RQ2a - How does the stage of advancement in SM adoption relate to the firm's ability to absorb external SM technological knowledge?* *RQ2b - Which are the technological and organizational factors that drive absorptive capacity in the context of Smart Manufacturing?*	**Objective 2** *RQ2c - How does absorptive capacity allow firms to progress to more advanced stages of Smart Manufacturing?* *RQ2d - How do managerial factors support knowledge absorption at different stages of Smart Manufacturing?*	**Objective 3** *R3a - What is the relation between competitive priorities and Smart Manufacturing advancement?* *R3b - What is the role organizational micro-foundations oriented to Smart Manufacturing play in the relation between competitive priorities and Smart Manufacturing advancement?*
Methodology	Empirical – multiple case study analysis (two polar cases)	Empirical – multiple case study analysis (four polar cases)	Empirical – multiple case study analysis (twelve case firms)	Empirical – survey (data from 234 firms)
Key findings	• Prime role of organizational factors in determining success of SM initatives • Advancement in SM requires absorption of externally generated technological knowledge	• Close interrelationship between level of absorptive capacity and stage of SM advancement • Development of absorptive capacity in the context of SM mainly hinges on organizational factors	• Evolve of managerial factors supports absorptive capacity at different stages of SM advancement • Need to align strategic priorities, knowledge base and SM technology policies	• Emphasis on multiple competitive priorities drives SM advancement • Organizational micro-foundations are pivotal in linking competitve priorities and SM advancement
Status	**Published** Arcidiacono, F., Ancarani A., Di Mauro C., Schupp, F., 2019. Where the rubber meets the road. Industry 4.0 among SMEs in the automotive sector. IEEE Engineering Management 47(4): 86-93.	**Accepted for publication** Arcidiacono F., Ancarani A., Di Mauro C., Schupp F., forthcoming. Stairway to heaven: how firms build absorptive capacity to succeed in Smart Manufacturing. In Florian Schupp, Heiko Wöhner (eds.), Digitalisierung im Einkauf. 2nd ed. Wiesbaden: Springer Gabler.	**Published** Arcidiacono, F., Ancarani A., Di Mauro C., Schupp F., 2022. The role of absorptive capacity in the adoption of Smart Manufacturing. International Journal of Operations & Production Management 42(6): 773-796.	**Published** Arcidiacono F., Ancarani A., Di Mauro C., Schupp F. Linking competitive priorities, Smart Manufacturing advancement and organizational micro-foundations. International Journal of Operations & Production Management. Doi.org/10.1108/IJOPM-06-2022-0355

Figure 1: Structure of the dissertation

CHAPTER 2. Investigating technological, organizational and environmental factors enabling Smart Manufacturing

2.1 Purpose

In the automotive sector, SM technologies are considered crucial to face a period of market turbulence and rapid technological change. However, while car makers and large Original Equipment Manufacturers lead the fourth industrial revolution, their smaller suppliers often lag behind. As a consequence of suppliers' technological constraints, the digitalization efforts of customers may not achieve full value creation potential. In this respect, investigation of enablers of SM adoption and progression has been recognized as important and timely. Building on the technology-organization-environment framework (Tornatsky and Fleischer, 1990), this chapter aims at shedding light on factors that facilitate implementation of SM initiatives among small and medium enterprises. To this end, two case studies of suppliers of a large component manufacturer operating in the automotive sector are used. Despite several similarities in terms of product range and markets, these firms are polar opposites when it comes to their digitalization status and, in this respect, are especially suited to the investigation of success factors for SM.

This chapter is adapted from *" Where the rubber meets the road. Industry 4.0 among SMEs in the automotive sector"*[5].

2.2 Positioning of the research

The automotive industry is currently undergoing a period of market turbulence and rapid technological change. This situation poses several challenges for firms in the sector. The pace of innovation has accelerated, product lifecycles have shortened, and uncertainty about future developments has increased (KMPG, 2019). Players in the industry now need to compress their development times to quickly react to changes in technological and market scenarios.

In this scenario, the adoption of new SM technologies assumes a strategic role to retain competitiveness. SM offers the prospects of relevant improvements in terms of productivity, efficiency, flexibility and quality of products.

While the automotive sector is at the forefront of SM implementation, new technologies find significantly wider application in large companies with respect to small and medium enterprises (SMEs henceforth). In the automotive sector, SMEs are major suppliers of components, parts, and sub-assemblies for larger companies. Failure to adopt SM on the supplier side may prevent customers from fullyimplementing inter-organizational digital practices.

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[5] Arcidiacono, F., Ancarani A., Di Mauro C., Schupp, F., 2019. Where the rubber meets the road. Industry 4.0 among SMEs in the automotive sector. IEEE Engineering Management 47(4): 86-93.

Full value creation potential of SM can be more fully exploited only if advanced technologies are applied uniformly along the entire supply chain. Each actor can optimize its internal value creation processes, and can be more competitive in terms of quality performance and prices charged to its customerswith these technologies.

Real time availability of data and inter-company connectivity pave the way for the creation of more collaborative supply networks. Sharing of real-time information related to demand, inventory, quality and production schedules, strengthens coordination among partners and lowers supply chain costs (Pereiraand Romero, 2017).

In order to further SM adoption along supply chains, it is important to identify key factors influencing SMEs' readiness to implement SM. In particular, the fact that technological transformations have been closely associated with a company's strategy requires understanding SME strategic decisions that might support SM implementation. For this purpose, we use two in-depth case studies concerning medium-sized firms operating in the automotive sector. The firms are similar in terms of size, market conditions, and initial SM investment efforts. However, because of different strategies pursued, one company is a benchmark when it comes to application of SM solutions, while the other one lags behind. Following a qualitative case-study research approach, the strategic determinants of two such different outcomes are highlighted.

2.3 Smart Manufacturing in the automotive sector

SM includes application in manufacturing contexts of such technologies as Cyber-Physical Systems (CPS), Internet of Things (IoT), Robotics, Big Data, and Cloud Computing. The aim is to create flexible and efficient production models, in which products and machines interact during manufacturing processes without any human intervention(Frank et al., 2019; Xu et al., 2018).

SM is a multifaceted concept encompassing three dimensions (Müller et al. 2018). First, highly digitized manufacturing processes, in which the availability of instant data arising from production lines allows decentralized, fact-based, decision-making. For instance, Volkswagen has recently partnered with Amazon Web Services to build its own industrial cloud, in which both products and production data will be stored. Second, use of CPS that provide a virtual representation of the physical world and permit live monitored, self-regulating operations. Audi has introduced a new modular production concept in its plant in Hungary that is enabled by Automatic Guided Vehicles controlled by artificial intelligence. Finally, inter-company connectivity, which favors integration along the value chain and quickens information sharing.

SM does not only affect processes but also creates value to customers. For instance, thanks to connected, flexible and highly automated production lines in the Sindelfingen plant, Mercedes

offers virtually endless product customization possibilities to clients ordering its flagship S-Class vehicles.
Smart products in automobiles increasingly embed computational capabilities, interact with the surrounding environment and have the capability to store and share data on their status and their use during their entire lifecycle. An exemplar case is represented by smart tires. Well-known tire manufacturers are experimenting with IoT-connected sensors and software platforms to measure and monitor tire performance. Early this year, Continental announced the launch of ContiConnect, a new tire-monitoring digital platform for commercialfleets.
Though expected benefits from adoption are considerable, SM implementation also poses several challenges. In particular, compared to larger enterprises, adoption might be particularly burdensome for SMEs due to constrained human and financial resources, and lack of specific technological competencies (Orzes et al., 2018). The next section introduces a framework for the analysis of factors influencing adoption.

2.4 SMEs and SM: factors impacting on adoption

Building on the tenets of the technology-organization-environment (TOE) framework (Tornatsky and Fleischer, 1990), we propose a classification of factors that affect SM adoption into three broad categories, according to their technological, organizational, or environmental nature (Table 1). Technological elements are tied to technological infrastructure and capabilities embedded within the firm or that are available on the market. Organizational aspects encompass the defining features of the firm, including its size, the availability of slack resources, and the approach to innovation adopted, leadership and management practices. Finally, environmental factors include the influence of supply chain partners, technology providers, competitors and other stakeholders. Jointly considered, the TOE factors contribute to define SME readiness to implement SM, which have been recognized to differ from the readiness requirements for large firms (Mittal etal., 2018).

Technological factors. SMEs might suffer from lack of up-to-date information technology (IT) infrastructure; a crucial prerequisite for any SM initiative. Next, lack of uniform technological standards determines compatibility issues and makes the integration between new and old equipment challenging and time consuming. In addition, the wide variety of SM solutions available on the market is at the root of a critical challenge for SMEs; namely compiling the right set of SM technologies to accomplish firms' objectives, while facing high uncertainty in technological development. This task may become daunting for SMEs because it is often coupled with limited qualified human resources to select andmanage SM.

Organizational factors. Constraints in accessing financial resources hinders capital investment and hence the adoption of new technologies. For instance, RFID applications are still relatively costly for SMEs to implement (Moeuf et al., 2018). Additionally, SMEs might be affected by insufficient commitment and support from top management (O'Halloran and Kvochko, 2015). A related reason is the difficulty to unambiguously quantify the benefits arising from SM implementation, which, combined with the pressure to optimize the use of scarce resources, could lead management to prefer alternative investments. Lack of managerial mind-sets oriented to SM will be reflected in a company culture that does not promote new technology adoption (Mittal et al., 2018). Lack of a supportive organizational culture may slow change acceptance from employees. Finally, fear of possible data breaches is another source of concern for top managers who, therefore, might be reluctant to invest and capitalize on inter-company connectivity (Culot et al., 2019).

Environmental factors. Upstream and downstream relationships in the supply chain influence SM adoption by SMEs. For example, excessive price pressures from client companies might reduce SMEs' financial slack and compromise the introduction of new technologies. Power imbalance and fear of losing bargaining power towards larger companies might lead smaller firms to oppose digital supply chain integration by sharing real- time data. Larger buyers could play an active role in fostering SM among SMEs suppliers by supporting them with expertise and tailored supplier developments programs.

Given the knowledge imbalance between SMEs and technology solutions providers, the latter might exploit their knowledge to their benefit. They might market cutting-edge solutions that go beyond SME needs or conversely by suggesting adoption of mature solutions that may rapidly become obsolete. Fear of opportunistic behavior from third party technology providers can hinder SM introduction. Finally, adoption of new technologies might be influenced by public institutions through national plans that envisageincentives for SMEs implementing SM.

Studies appear to link the slow adoption of SM by SMEs to uncertainties regarding technological options available, internal and external risks stemming from adoption, and potential benefits. These uncertainties may be driven by lack of planning and lack of long-term perspectives within SMEs (Moeuf et al., 2018). Since investment in technology adoption is a top-down decision within companies, it is worth exploring how a strategic vision of SM may have engendered different configurations of TOE factors, therefore leading to different degrees of implementation of SM.

Table 1: Overview of TOE factors influencing SM adoption among SMEs

Technological factors	• IT infrastructure • Existence of multiple standards • Complexity linked to variety of technologies available • Availability of specialized human resources
Organizational factors	• Financial constraints • Top management commitment • Supportive organizational culture • Employees' acceptance of change
Environmental factors	• Price pressures from customers and power imbalance • Collaboration with buyers • Competitive environment • Relation with technology suppliers • Institutional factors

2.5 Research design

In what follows, we present two case studies referring to middle-sized enterprises with equivalent initial TOE conditions but which have currently achieved significantly different levels of SM implementation. The case analysis will try to highlight the success factors tied to management strategic decisions.

The case companies reside in Northern Italy. Both are suppliers of a large multinational company operating in the automotive component sector. Their buyer sought to strengthen adoption of SM technologies along the supply chain. The buying company carried out an assessment of its suppliers, exploring challenges faced in SM adoption process. We asked a senior purchasing manager to identify two suppliers of the multinational company. One case represents successful adoption and another case had an unsatisfactory adoption of SM.

In a first step, preliminary information on company characteristics, SM technologies implemented, and future plans was gathered through an online questionnaire administered to the CEOs of the two suppliers. This information was then complemented with in-depth, structured interviews Top management, the chief technology officer (CTO) and quality managers of the firms participated in the interviews.

2.6 Company characteristics

Firm A has 40 years of experience in the manufacturing of thermoplastic components. It produces exclusively for the automotive sector. About 200 employees work for the enterprise, which has an annual revenue of 27 million Euro. Until 2006, basic IT infrastructure was in place and production lines were not automated. The company had no previous experience related to the application of cutting-edge technologies. Up to that date, there was no specific position within the company to plan and manage projects concerning new technologies. Furthermore, no partnerships with universities or technology suppliers were established. Since then, the firm has focused on digitizing internal processes and introducing automation in its production lines. To do so, the enterprise has appointed its R&D manager in charge for envisioning and managing SM projects. They also partnered with selected technology suppliers. Currently, orders from customers are received via electronic data interchange (EDI) and automatically uploaded on their enterprise resources planning (ERP) system. All machines are connected to the manufacturing execution system (MES). Real time data on the production status and critical- to-quality parameters are collected and analyzed to reduce down-times and detect early stage quality issues. Use of automation is widespread. Over 70% of the machines are fully automated and operate 24 hours a day and 7 days a week. Machines, which are organized in manufacturing cells, ensure that the correct raw material is used and stop automatically once the required number of pieces has been manufactured. At the end of the production cycle, critical parts undergo final quality checks that rely on vision systems and are performed on 100% of the products. Other SM projects are currently underway using CPS technology to continuously vary input parameters for machines. The aim is to compensate for variations in environmental conditions and raw material properties, which could negatively affect the quality of parts produced. The opportunity of introducing handling robots is being evaluated. This decision is driven by the goal to improve efficiency and reduce the time spent by operators in non-value-adding activities.

Firm B has 40 years of experience in the manufacturing of mechanical components for the automotive industry. The headcount is approximately of 170 workers and annual revenue is 21 million Euro. Similar to firm A, up to 2005, firm B relied on a basic IT infrastructure and had no applications of advanced technologies in its manufacturing lines. There was no internal expertise regarding advanced technologies nor ongoing research to envision possible uses. The firm had never cooperated before with universities or technology providers to investigate the potential of new technologies and of their application. Since 2005, pressed by the need to streamline its logistics, reduce lead times and improve quality, the firm acquired an automation company and exploited its expertise to automate its logistics and quality checks. The firm has introduced two automated warehouses, in which finished goods and raw materials (coils) are stored. The firm also invested in quality monitoring and improvement. Before entering production, coils undergo 100% camera checks to detect superficial imperfections that could determine quality issues at subsequent production stages. Despite these early initiatives, the pace of SM adoption has slowed down. Firm

B is currently far from representing a benchmark in terms of SM applications and digitization of processes. The absence of an integrated ERP and EDI connection means that orders from customers are received by emails and manually uploaded to an internal information system for exclusive use of the sales department. A list of new orders is printed daily and delivered to the production manager, who creates a production schedule and transmits it to the operators responsible for the machines. An MES has not been introduced. Production data are stored at the machine level, but not analyzed. Firm B has no structured plans to implement additional SM projects in the near future. The CEO made the following statement:"*We had started to plan other applications, but this kind of projects are time-consuming andthere are always more pressing matters to dealwith.*"

2.7 Cross-case analysis

We next assess the TOE factors role in SM implementation and intention to adopt in the future. This assessment will shed light on whether distinct strategies have supported SM implementation. Technological elements did not emerge as having any significant explanatory power. None of the interviewees cited lack of updated IT infrastructure, compatibility issues, or high search costs of technological solutions ashurdles.

For organizational factors, a fundamental difference in the management approach to SM of the two companies emerged when interviewees were asked to describe the circumstances prompting them to embrace newtechnologies.

When invited to retrace the steps leading to the decision to automate the warehouse, the management of Firm B stated: "*Prior to the introduction of the automated warehouse, we were forced to tell customers that we would have fulfilled their requests with delay, despite having finished goods in stock. In fact, the situation was so tangled, and parts were placed so far away that we couldn't physically take the products. At that point, we decided that it was time to act, because without an efficient warehouse, it is impossible to promptly satisfy customer needs and we are aware we are the weakest link in the supply chain*".

The fact that transitions to new technology were prompted by crisis situations seems to be a recurrent pattern in the case of Firm B. In this respect, the development of the quality vision system was another illuminating example: "*We used to receive many complaints per year due to scratches on products and several trucks fully loaded with nonconforming parts were returned to our plant. In those instances, we had to check 100% of the parts manually! That's why we developed this system that detects superficial scratches on coils and, in case, stops production*".

When asked whether financial constraints had led to this reactive strategy of adoption, the interviewees stated that finding money had never been an issue, due to the availability of national level public subsidies.

In contrast to the reactive approach of Firm B, which leads to actual implementation of SM initiatives only because of external customer pressures, Firm A offers a more proactive attitude: "*In the first place, we as a company see the benefits of process innovation, in the sense that we are glad to improve our processes and the quality of our products". As a result:* "S*tep by step, over the years, our company has adopted several automation systems. In the meantime, we added the MES and we gradually understood its use, its advantages and how to fully exploit it. Nowadays our production isarranged in automated cells".*

The relentless, step-by-step approach, adopted by Firm A has led to a pervasive application of SM technologies within the firm and has averted major implementation roadblocks: *"So far, we have been able to successfully complete every SM project we have started. We found ourselves at an impasse under nocircumstances".*

From an organizational perspective, the reactive vs. pro-active approach to technology management was not the only relevant managerial factor to support a continuous adoption of SM. As emphasized by research linking organizational culture to technology adoption and performance (e.g. Nahm et al., 2004), an organizational culture with strong beliefs in investing in technology tends to co- exist with encouragement to workers to work in innovative ways. In this direction, in Firm A change acceptance among workers emerged as a second element with significant positive consequences for the success of the adoption process. To put it in Firm A's words*: "Change is the result not only of machines and systems, but it is rooted in a shift in workingroutines of our employees*".

Fostering change acceptance among employees is not an easy task if not supported by an organizational culture oriented to the continuous upgrading of technological competences, as stated by the CEO of Firm B*: "Changing workers' mentality and behavior has been one of the most difficult hurdles to overcome".*

His frustration clearly emerged during the interview: *"You might be able to push workers to the next level, but then, if you lose focus for a moment and the progress is not continuous, theygo back to the starting point. It is exhausting!".*

Because of a top-down, intermittent introduction of SM innovation, which fails to fully engage employees, acceptance of new technologies might be hampered:*"When we introduced the camera system, workers used to alter its settings. "The camera system keeps on stopping the line, it is not possible!" This was their thinking!"*

To overcome the same barrier, Firm A has opted for early involvement of workers in the process of change. The R&D manager of Firm A reported: *"We have realized that our employees are crucial actors in the process of change. That is why we involve them since the beginning. In our organization, employees are positive viruses ofchange".*

However, early involvement is not enough, if not paired with training, in the view of Firm A: *"In SM initiatives, the development of human capital is of the utmost importance. So, in parallel to investments in technological assets, we support our employees with specific training".*

As a result, the transition to more advanced production systems appears to be much smoother in Firm A than in Firm B, as stated by the R&D manager of Firm A: *"Once the introduction of new systems is complete, our employees often ask themselves:" How could I manage before?!"*

Divergences between Firm A and Firm B are not limited to organizational aspects but also encompass environmental factors. The two companies face similar environmental conditions as far as competitive pressures are concerned, given that they have to battle with competitors located in countries characterized by lower costs of labor and feel they must offer their customers higher quality to compensate for higher costs (Ancarani and Di Mauro, 2018). Strategic decisions pursued in terms of relationships with technology providers have emerged as an additional key determinant of the different status of implementation of SM. Firm B preferred to build know-how internally, rather than establishing cooperation with technology providers. In this respect, the CEO of the company reported:"*Ten years ago, we acquired a small automation firm. We did so to develop know- how internally and to ensure that it remains exclusively ours".*

The fear of falling prey to opportunistic behavior from technology providers laid at the root of this choice: *"Had we opted to collaborate with an external technology provider, the co-developed solution could have been re-sold by our partner. Results of our work would have been freely available to our competitors who could have benefited from it."*

At face value, the strategy pursued by Firm B seems to have paid off: *"In the case of the camera system, we initially turned to an external company with specific expertise, but they quoted us over 70,000 € and the final result was not guaranteed. Then we decided to do everything on our own. We succeeded and, in the process, we saved 50,000 €. It has been a really satisfying accomplishment!"*

Nevertheless, at a second glance, short-term successes was offset by long-term disadvantages, as it emerges from the words of firm's A R&D manager: *"In the past, we tried to develop SM solutions solely relying on our internal know- how, but we found out that it is not a winning strategy in the long run. It requires too much time and there is a substantial risk of being left behind. Nowadays, advancements have to be fast, especially in this field".*

To avoid lagging behind in terms of advanced applications and, at the same time, to profit from specific expertise, Firm A has: *"developed long-term partnership with few technology suppliers"*. The possibility for co-developed solutions to be made available on the market at the end of the collaboration process is agreed since the beginning by both partners and, as a result, this seems to be a win-win condition.*"The advantage is twofold"* claimed the R&D manager of Firm A *"as we benefit from solutions tailored to our needs and the technology supplier has real-life examples of successful applications of the products, which can be showed to prospective customers"*.

In summary, a pro-active approach to technological innovation, early involvement to foster change acceptance among employees and strategic relationships with technology providers have emerged as factors that played a role in determining the different implementation of SM technologies in the cases at hand. Table 2 summarizes these findings.

Table 2: Overview of the findings

Factor	Nature	Firm's A strategy	Firm's B strategy
1. Approach to technological innovation	Organizational factor	Proactive approach to innovation, independent from external pressures	Reactive approach to innovation, dependent on external pressures
2. Need to foster changeacceptance among employees	Organizational factor	Early involvement of employees and trainingto provide support	Top-down approachto change
3. Relationship with technology suppliers	Environmental factor	Long-term partnership with selected technology providers todevelop tailored solutions	No partnership with technology suppliers. Reliance on internal competencies

CHAPTER 3. Linking absorptive capacity and Smart Manufacturing

3.1 Purpose

As hinted by the previous chapter, prospective SM adopters are expected to repeatedly search and process new, specialist, and sometimes distant technological knowledge, which is usually generated outside the boundaries of traditional manufacturers (Kranz et al., 2016). In this respect, it can be conjectured that absorptive capacity (AC henceforth), i.e. a dynamic capability underpinning firms' ability to acquire, assimilate, transform and exploit external knowledge (Zahra and George, 2002), is a crucial capability that firms undertaking the SM transformation should possess. Based on this observation, this chapter builds on SM and AC literature to develop a conceptual framework linking the stage of SM adoption, the levels of AC and technological and organizational factors that support SM knowledge absorption. Evidence from four in-depth case studies is used to explore the applicability of the framework and to pinpoint factors that have a relevant impact.

This chapter is adapted from: *"Stairway to heaven: how firms build absorptive capacity to succeed in Smart Manufacturing"*[6].

3.2 Positioning of the research

Several manufacturing industries are currently undergoing a period of market turbulence and rapid technological change that requires keeping pace with the accelerating rate of innovation, while concurrently reducing costs and maintaining high quality standards (Kuhnert et al., 2017; Lasi et al., 2014). In this context, SM technologies are considered strategic to successfully navigate these challenges, given that they promise to deliver significant improvements in operational and financial performance (Bag et al., 2021; Bai et al., 2020; Dalenogare et al., 2018; Tortorella et al., 2020). Although the definition of SM is still controversial (Culot et al., 2020), there is general agreement that it encompasses the interconnection of advanced technologies to enable autonomous production systems, in which process parameters are automatically adjusted to allow for multiple types of products and changing conditions (Kagermann et al., 2013; Moeuf et al., 2018).

To date, challenges such as the identification of the right portfolio of technologies (Parthasarthy and Sethi, 1993) and the fact that breakthroughs require the integration of multiple and complementary technologies (Autry et al., 2010; Frank et al., 2019) have determined a fragmented diffusion of SM. In turn, fragmented diffusion of SM technologies has the potential to jeopardize the benefits tied to their use, as full value creation potential of SM can be exploited only if partner organizations are

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[6] Arcidiacono F., Ancarani A., Di Mauro C., Schupp F., forthcoming. Stairway to heaven: how firms build absorptive capacity to succeed in Smart Manufacturing. In Florian Schupp, Heiko Wöhner (eds.), Digitalisierung im Einkauf. 2nd ed. Wiesbaden: Springer Gabler.

aligned on advanced stages of adoption (Arcidiacono et al., 2019). In this respect, it is valuable to shed light on capabilities that firms need to develop to successfully embrace the digital transformation.

A long research tradition has recognized that AC plays a crucial role in allowing organizations to adopt technological advancements (Cohen and Levinthal, 1994; Zahra and George, 2002). In the context of SM, since progression requires the incorporation of increasingly complex blocks of technologies (Frank et al., 2019), prospective adopters are expected to iteratively search and process new, specialist, and sometimes distant technological knowledge generated outside the boundaries of the firm (Kranz et al., 2016), and to integrate it with their knowledge base. These features lead to conjecture that AC is a crucial capability that firms undertaking the SM transition should possess. However, to date little research has investigated the relation between AC and SM adoption (Lorenz et al., 2020; Mahmood and Mubarik 2020; Müller et al., 2021). In particular, limited attention has been devoted to the investigation of how the ability to capture and transform SM-related external knowledge evolves to allow firms to progress in the adoption of SM. Additionally, there is insufficient understanding on which firms' technological and organizational factors can act as forerunners to shape the capacity to acquire and transform SM knowledge (Mittal et al., 2018). Shedding light on the role of AC in sustaining SM can increase the understanding of how firms may acquire SM knowledge effectively and efficiently and on ways to make the transformation of value chain processes swifter and smoother.

This study contributes to fill the abovementioned research gap by addressing the following two research questions:

RQ2a: How does the stage of Smart Manufacturing adoption relate to the firm's ability to absorb external technological knowledge?

RQ2b: Which are the technological and organizational factors that drive absorptive capacity in the context of Smart Manufacturing?

To answer these questions, we contextualize the general theory of AC to SM and propose an integrative framework that identifies AC's antecedents and links components of AC to stages of SM adoption. The framework is then used to guide the interpretation of multiple qualitative case studies and to formulate propositions to be tested in future research.

Results support the role of AC in allowing firms to achieve more advanced stages of SM. They further highlight the importance of adapting structures and processes at the organizational level in order to sustain AC.

The study makes multiple novel contributions to the SM operations management literature and to practice. First, results contribute to the understanding of the role of AC in innovation processes, by extending and contextualizing the analysis to the case of SM. Next, although literature has identified an extensive list of factors influencing SM adoption, they have not been typically linked to the firm's ability to acquire and apply external technological knowledge and combine it with own previous knowledge. From a practical viewpoint, findings provide guidance to manufacturing executives who are engaged in the adoption of SM, by throwing light on crucial technological and organizational factors that need to be developed or enhanced to support the absorption of new technological knowledge.

3.3 Background

3.3.1 Smart Manufacturing and factors influencing its adoption

SM envisions the widespread application of technologies related to digitalization, automation and connectivity in manufacturing contexts (Brettel et al., 2014; Fatorachian and Kazemi, 2018; Kagermann et al., 2013). Although its key principles and enabling technologies are not entirely novel (Culot et al., 2020), SM is considered a new industrial paradigm in virtue of the unprecedented integration between physical objects and digital technologies, which allows highly connected manufacturing systems (Dalenogare et al., 2018; Xu et al. 2018) and paves the way for operations that can be controlled and optimized in real time (Moeuf et al., 2018).

Research consistently identifies SM as a source of competitive advantage, given the ability of these technologies to generate performance improvements in terms of productivity, time-to-market, flexibility, inventory management and supply chain management (Delic and Eyers, 2020; Dev et al., 2020; Hofmann and Rüsch, 2017; Wamba et al., 2017). These improvements may prove vital for industries burdened by increasing R&D costs and declining margins (McKinsey, 2013), reduced product life cycles (Loh et al., 2019) or managing complex supply chains (Thun and Hoenig, 2011).

More advanced stages of SM adoption require the integration of multiple technologies, which allow confer to firms' processes increasingly sophisticated capacities (Ancarani et al., 2019; Frank et al., 2019; Moeuf et al., 2018). Monitoring is the simplest capacity, whereby firms exploit SM to supervise the status of their processes and to issue alerts. By linking the reality of products and machines to the internet environment (Lu, 2017; Tao et al., 2018;), the Internet of Things (IoT) is instrumental in enabling real-time, constant monitoring of products and processes (Civerchia et al., 2017; Lee and Lee, 2015). The control capacity additionally allows the definition of performance thresholds based on historical data and simulation models. Connected systems monitor and control machines and products and leverage big data from the physical processes to update the virtual models (Frank et al., 2018). To build optimization capacities, firms leverage on cloud computing and cybersecurity solutions, which guarantee safe online data storage and real-time retrieval (Saberi et al., 2019; Yu et al., 2015). In addition, big data analytics offer predictions and expose underlying trends through in-depth analysis of data (Chen et al., 2016; Cheng et al., 2017). Finally, the most advanced SM adopters confer autonomy to manufacturing systems by exploiting machine learning and artificial intelligence and thus minimizing the need for operators' decisions and interventions (Lee et al., 2018).

The emergent research stream on SM concurs that both technological and organizational factors are key to its adoption (Chen et al., 2015). Drawing from recent contributions on SM in the fields of Operations Management and Innovation Management, Table 3 provides an overview of the main influencing factors. Several research studies emphasise the importance of technological factors such as firms' IT infrastructure, inter-operability issues and workers' digital competences. Among organizational factors, strategy and leadership (Schumacher et al., 2016) and a culture supporting collaborations and the creation of SM ecosystems (Benitez et al., 2020) are critical for SM maturity. Structural elements supporting implementation have been identified in organizational agility and in the creation of roles specifically assigned to SM (Veile et al., 2019). Finally, firms' processes need to adapt to SM implementation. In this direction, crucial factors include conscious operational planning of SM projects (Horváth and Szabó, 2019) and information sharing with workers (Moeuf et al., 2020).

Table 3: Factors influencing SM adoption

Technological factors	Technologies in use and knowledge base	Updated IT infrastructure (Arcidiacono et al., 2019; Kamble et al., 2018; Moeuf et al., 2020)
		R&D activities (Majumdar et al., 2021)
		Evaluation of technological compatibility (Kamble et al., 2018; Kiel et al., 2017; Mueller et al., 2017)
	HR competencies	Employees' digital competencies (Kamble et al., 2018; Mittal et al., 2018; Orzes et al., 2020; Veile et al., 2019)
Organizational factors	Strategy and Leadership	Identification of strategic goals and linked SM technologies (Moeuf et al., 2020; Raj et al., 2020)
		Leadership support (Arcidiacono et al., 2019; Moeuf et al., 2020; Orzes et al., 2020; Schumacher et al., 2016)
	Organizational culture	Culture of openness to external collaborations (Benitez et al., 2020; Mittal et al., 2018; Moeuf et al., 2020)
	Structure	Agile organizational structure (Veile et al., 2019)
		Specific roles for SM (Horváth and Szabó, 2019; Moeuf et al., 2020; Tumbas et al., 2018; Zheng et al., 2019)
		Cross-functional project teams (Veile et al., 2019)
	Processes	Operational planning for implementation (Horváth and Szabó, 2019)
		Communication about SM projects (Moeuf et al., 2020; Veile et al., 2019)
		Training (Veile et al., 2019; Horváth and Szabó, 2019)

3.3.2 Absorptive capacity and its antecedents

AC is the ability to recognize and assimilate new external knowledge, integrate external and internal knowledge and develop applications for commercial ends (Cohen and Levinthal, 1990). Zahra and George (2002) view AC as a four-dimensional process flow: acquisition, assimilation, transformation, and exploitation. Acquisition and assimilation define firms' potential absorptive capacity (PAC), which makes organizations capable of searching and understanding new external knowledge. Transformation and exploitation define realized absorptive capacity (RAC), which reflects firms' ability to combine external and internal know-how and exploit it to gain competitive advantage. Both PAC and RAC are necessary in order for organizations to benefit from externally generated knowledge (Zahra and George, 2002). In fact, firms concentrating exclusively on PAC are able to update their knowledge base but fail to reap its benefits. Conversely, organizations focusing on RAC may have a short-lived competitive edge, being prone to fall into a competence trap (Ahuja and Lampert, 2001; Jansen et al., 2005; Volberda et al., 2010). Although variants have been proposed (Lane et al., 2006; Patterson and Ambrosini, 2015; Todorova and Durisin, 2007 among others), the distinction PAC-RAC has been confirmed by several studies (Ali et al., 2016; Brettel et al., 2011; Flatten et al., 2015; Jansen et al., 2005; Volberda et al., 2010).

A literature search of the main contributions in the AC field has led to the identification of the main antecedents of PAC and RAC, which are summarized in Table 4. Research has recognized the reliance of both PAC and RAC on firms' prior knowledge endowment (Cohen and Levinthal, 1990), on organizational mechanisms (Jansen et al., 2005; Van den Bosch et al., 1999; Volberda et al., 2010) and on supportive leadership (Flatten et al., 2015). Some antecedents emerge as distinctive of either PAC or RAC. Specifically, PAC is contingent on exposure to diverse and complementary external knowledge sources (Lewin et al., 2011; Spithoven et al., 2011) and on experience with knowledge search (Fosfuri and Tribò, 2008). Further, PAC is linked to coordination capabilities such as cross-functional interfaces aiding internal knowledge exchange and assimilation (Jansen et al., 2005). Unlike PAC, RAC is sustained by the codification of practices for technology implementation (Bouguerra et al., 2021; Jansen et al., 2005) and by socialization practices. In this direction, knowledge transformation processes are enhanced by internal networks enabling peer-to-peer interactions (Jansen et al., 2005) and by information communication throughout the organization on the value of new practices (Lenox and King, 2004).

Table 4: Intra-organizational antecedents of PAC and RAC

Categories	Antecedents of PAC and RAC	PAC	RAC
Exposure to diverse and complementary external knowledge	Broadly scanning for new knowledge (Lewin et al., 2011; Volberda et al., 2010)	X	
	Gatekeepers or boundary spanners (Cohen and Levinthal, 1990; Volberda, 1996)	X	
	Interaction with technology intermediaries (Spithoven et al., 2011)	X	
Knowledge base and competencies	Prior related knowledge (Cohen and Levinthal, 1990; Lane et al., 2001; Volberda 2010)	X	X
	R&D activities (Cohen and Levinthal, 1990; Fosfuri and Tribó, 2008; Xia and Roper, 2008)	X	
	Experience with knowledge search (Fosfuri and Tribó, 2008; Zahra and George, 2002)	X	
	Employees' skills (Xia and Roper, 2008)	X	
	Training and personnel development competence (Lane et al., 2001)		X
	Adaptive and integrative capacities (Garrety et al., 2004; Robertson et al., 2012)		X
Organization system	Autonomy of middle managers (Lewin et al., 2011; Rotemberg and Saloner, 2000)		X
	Formalization (Bouguerra et al., 2021; Jansen et al., 2005)		X
Social integration mechanisms	Coordination capabilities (Bouguerra et al., 2021; Jansen et al., 2005; Van den Bosch et al., 1999; Volberda et al., 2010)	X	X
	Socialization capabilities (i.e. connectedness, socialization tactics) (Bouguerra et al., 2021; Jansen et al., 2005)		X
	Internal information communication from managers (Lenox and King, 2004)		X
Leadership	Transformational and transactional leadership (Flatten et al., 2015)	X	X
	Leadership resources and support for subordinates' learning (Li et al., 2018)	X	X

3.4 Building AC for SM

Although operations management research on SM is rapidly gaining momentum (Culot et al., 2020), there are still no studies linking SM adoption to the capability of the firm to absorb external knowledge and exploring factors that can support absorption. Building on the two literature streams discussed in Section 3.3, this section tries to fill this gap by conceptually elaborating on potential technological and organizational antecedents of PAC and RAC that are relevant in the context of SM adoption. Our elaboration was guided by a "horizontal contrasting" approach (Fisher and Aguinis, 2017), whereby aspects of a theory are generalized to a new context in order to gain a deeper understanding of whether and how the theory should be adapted to fit the specific context. Specifically, starting from the antecedents of AC in Table 4, we searched for conceptually equivalent groups of factors influencing SM adoption in Table 3, which could be probed as a source of PAC and RAC in the context of SM. Next, we identified factors that the SM literature considers relevant for adoption that had no equivalent in terms of AC antecedents. Finally, we searched for antecedents of AC in Table 4 that had no corresponding concept in Table 3. The research team discussed whether these factors could generate either PAC and/or RAC. The identification of these factors is of interest because they signal specificities in the way AC must be conceptualized in the context of SM.

3.4.1 Enabling SM adoption through PAC

PAC has been linked to technology-related factors such as prior knowledge (Volberda et al., 2010; Zahra and George 2002), experience with knowledge search (Fosfuri and Tribó, 2008), and workforce competences (Xia and Roper, 2008). Firms endowed with base digital technologies such as Industry 3.0 IT infrastructure, data security systems and base Industrial IoT possess the necessary knowledge base over which SM competences can be built (Kamble et al., 2018). In addition, firms that have actively experimented with digital technologies can better understand the knowledge embodied in SM technologies (Nakayama et al., 2020). Further, R&D activities can help firms pivot to SM, because they often imply past collaborations with universities and other sources of innovation (Majumdar et al., 2021). Finally, employees' digital competencies may support the acquisition of process-dependent systems in production, logistics and procurement and the process of selection of new software and hardware (Flores et al., 2020; Xia and Roper 2008).

Successful adoption of SM requires the alignment of technology policies with strategic priorities (Zahra and Covin, 1993). Building on findings in SM research (Moeuf et al., 2020), we posit that clear strategic goals to be achieved through SM and deliberate planning of its introduction enhance PAC, because they contribute to orient firms' search of relevant knowledge. In the same direction, leaders competent in SM (Moeuf et al., 2020) and favouring learning opportunities (Li et al., 2018), shape a positive environment for the digital transformation (Tortorella et al., 2020) and inspire followers to acquire and assimilate SM knowledge (Flatten et al., 2015). Likewise, organizations open to external collaborations engage in wider scope environment-scanning and engage in multiple partnerships (Benitez et al., 2020; Mittal et al., 2018), therefore gaining access to the diversity of knowledge involved in SM adoption.

PAC depends on organizational structures supporting knowledge absorption. Along these lines, SM-specific roles can bridge technological solutions available on the market and firms' technological needs. In particular, the appointment of roles acting as boundary-spanners and gatekeepers (Cohen and Levinthal, 1990) can channel the acquisition of technological knowledge by translating external SM information into a form understandable to internal stakeholders. Next, by promoting knowledge exchange and the development of new perspectives, cross-functional teams comprising diverse expertise are important for external knowledge search and assimilation (Jansen et al., 2005; Veile et al., 2019).

3.4.2 Enabling SM adoption through RAC

Given the importance of prior related knowledge for both PAC and RAC (Volberda, 2010), the IT endowment can proxy the firm's capacity to transform and exploit new SM technologies, by augmenting capabilities for data collection and sharing (Kamble et al., 2018; Osterreider et al., 2020). Related to the above, compatibility issues between legacy technologies and SM may critically slow down the integration and exploitation of new technologies, therefore requiring the development of integrative capacities (Garrety et al., 2004; Robertson et al., 2012). To illustrate, because existing IT infrastructures are often fragmented, smart production relying on cyber-physical systems (CPS) needs to be developed by adapting and integrating a range of components (Deloitte, 2017). The need for integrative capacities (Robertson et al., 2012) is further magnified because interoperability is required to stretch not only to the different machines and intra-firm functional systems, but also to supply chain partners.

Employees' digital competencies affect exploitation of SM in addition to assimilation (Kamble et al., 2018; Mittal et al., 2018; Orzes et al., 2020). To exemplify, connected manufacturing systems require the presence of human controllers possessing ICT know-how (Veile et al., 2019) and problem-solving capabilities (Kiel et al., 2017). Similarly, the exploitation of the industrial IoT potential requires expertise in data analytics to detect patterns in data (Kiel et al., 2017).

Given that decentralized decision-making is one of the pillars of SM, leadership offering resources such as individualized support and autonomy (Flatten et al., 2015) and agile organizational structures that guarantee decision autonomy to middle managers (Lewin et al., 2011; Rotemberg and Saloner, 2000) can sustain RAC.

RAC also depends on a deliberate approach to SM adoption. Firms that carry out operational planning, by formally defining steps and roles for project implementation, are more likely to successfully integrate new technologies (Horváth and Szabó, 2019). In this direction, senior officers such as R&D managers or digital officers are called to play an important role by monitoring the roadmap for the introduction of different SM technologies and their integration across activity domains (Tumbas et al., 2018; Zheng et al., 2019). Further, competent project managers leverage their knowledge to adapt SM to the firm's needs and legacy equipment, thereby defining the needed level of integration and adaptation (Horváth and Szabó, 2019; Moeuf et al., 2020).

RAC is also sustained by social integration mechanisms (Bouguerra et al., 2021; Patterson and Ambrosini, 2015). In particular, cross-functional teams can facilitate SM cross-functional integration within the smart factory by addressing inter-operability issues and by facilitating technology transfer across application contexts (Flores et al., 2020). Further, given that SM engenders significant changes in work routines, stemming from transparency and autonomy requirements or from human-automation symbiosis, promoting social connectedness among workers and developing trust through effective information provision by managers may ease the transformation process (Jansen et al., 2005; Lenox and King, 2004). Finally, training programs (Lane et al., 2001) support SM knowledge exploitation by providing workers with the necessary digital skills (Arcidiacono et al., 2019; Tortorella et al., 2020) but also with communication competencies that facilitate collaboration (Veile et al., 2019).

While the factors previously discussed appear to be positively related to RAC, we expect that an ambiguous role in SM exploitation is played by process formalization. On the one hand, the SM decentralization logic requires transversal skills and increased employee autonomy, leading to foresee a negative impact of formalization on RAC. On the other hand, by generating new controlling opportunities, SM exploitation requires highly formalized job designs (Cimini et al., 2021).

Figure 2 summarizes the above discussion with a framework that integrates results from AC and SM research. The framework engenders that PAC and RAC have specific antecedents in the context of SM. In turn, PAC and RAC influence the SM advancement stage.

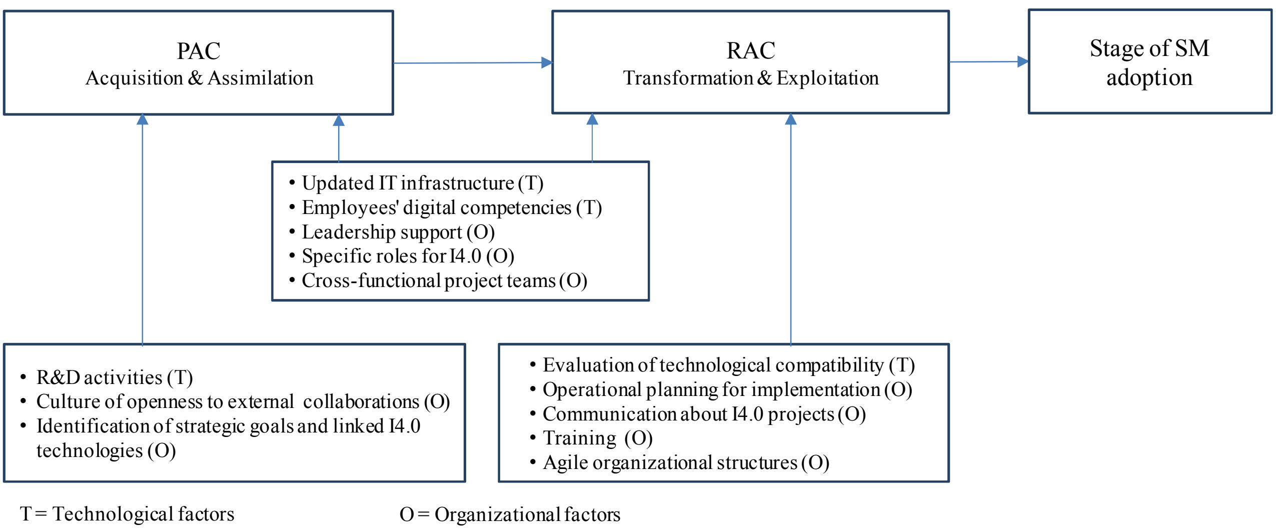

Figure 2: Conceptual framework

3.5 Research Methods

Multiple case studies were built to investigate how AC relates to firms' stage of SM adoption and how firms develop AC in the context of SM. For each case, information was retrieved from multiple sources and triangulation was used to enhance construct validity (Gibbert et al., 2008; Yin, 2014). The research strategy is explained in the following sections and summarized in Figure 3.

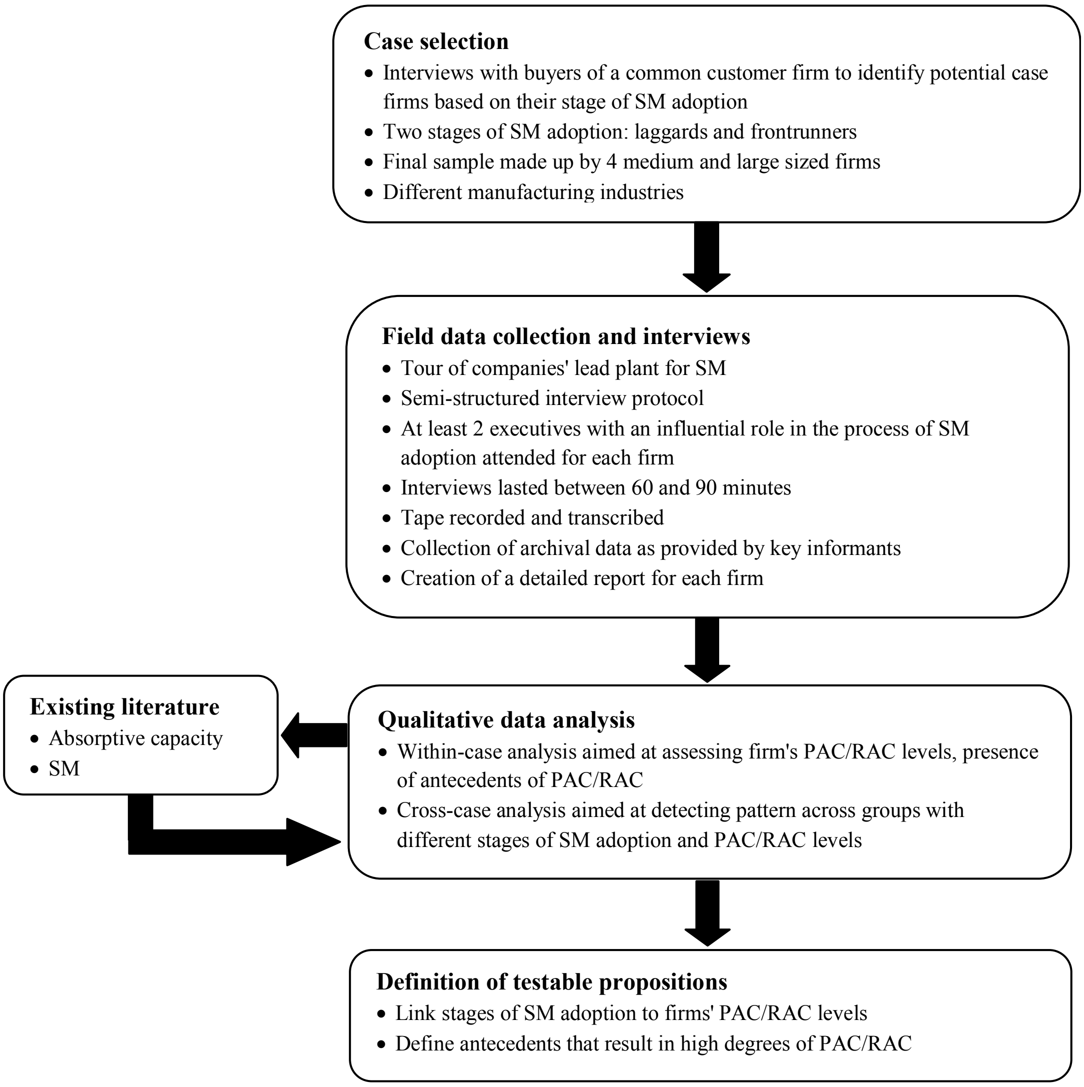

Figure 3: Overview of the research strategy

3.5.1 Case selection

Cases were selected among first tier suppliers of a large automotive OEM following the theoretical sampling principle (Eisenhardt and Graebner, 2007). Using the classification of capacities enabled by SM proposed by Moeuf et al. (2018) and presented in Section 3.3.1 (Monitoring, Control, Optimization, Autonomy), two groups of firms were defined according to the stages of advancement in SM: (i) laggards, using SM with the simple goal of monitoring internal operations; (ii) frontrunners, which exploit SM to optimize operations and to confer some autonomy to their production systems. Several supplier managers and buyers of the customer firm were asked to identify replicated cases of laggards and frontrunners among supplying firms (Yin, 2014). Interviews led to the identification of four potential case firms, which accepted to participate in the qualitative study and constitute the sample. Case firms are medium and large-sized (Table 5), are located in Northern Italy and belong to different industry sectors.

Table 5: Overview of case companies

	Name (size)	**Manufacturing industry**	**Informants' job titles**
Frontrunners	Frontrunner1 (Large)	Fabricated metal products	CEO, CDO, Quality Manager, Production Manager
	Frontrunner2 (Medium)	Plastics products	CEO, R&D Manager, Quality Manager
Laggards	Laggard1 (Large)	Rubber products	Plant Manager, R&D Manager, Quality Manager
	Laggard2 (Medium)	Fabricated metal products	Quality Manager, Production Manager, Sales Manager

3.5.2 Field data collection and interviews

The research team also carried out field tours of each company's lead plant for SM with the aim to obtain a more robust understanding of firms' SM technologies adopted and of applications and to cross-validate the initial classification of case firms. Field notes were used as input for the interviews and the final case reports. Next, interviews were conducted according to a semi-structured protocol grounded in the framework in Figure 2. The protocol started with open-ended questions about SM technologies adopted or in-progress and on adoption processes. The main body of the interview explored technological and organizational factors acting as barriers and enablers of SM knowledge absorption. In particular, the research team probed knowledge search and acquisition modes, which entailed the understanding of the range and type of collaborations with technology partners. Next, assimilation, transformation and exploitation were discussed with specific references to the importance of previous knowledge, digital skills, leadership support, structures, and processes. In order to avoid the single respondent bias (Golden, 1992; Miller et al.,1997), the research team interviewed at least two respondents who had an influential role in the adoption of SM at each firm. A total of 12 in-depth interviews were carried out. Conversations last 60 to 90 minutes, were tape recorded and then transcribed (Mero-Jaffe, 2011).

Additional archival data supported the preparation of case reports. Final case study reports and interviews transcripts were then reviewed by companies' informants to ensure reliability of data (Mero-Jaffe, 2011).

3.5.3 Qualitative data analysis

Standard practice was followed by undertaking within-case analysis first, followed by between-case analysis (Eisenhardt, 1989). Two of the authors independently performed the within-case analysis. Both AC and SM literature were incorporated at this stage to guide the team in the interpretation of data (Eisenhardt, 1989). The within-case analysis was articulated in three phases. In the first phase, the PAC and RAC levels of case firms were measured. The researchers extracted from the data a list of indicators, which were grouped according to the four dimensions of AC (Figure 4). Firms' PAC and RAC were classified as high or low based on the following criteria: (1) high PAC/RAC firms have developed all four dimensions of AC, as exemplified by the presence of at least one indicator for each dimension; (2) low PAC/RAC firms have not developed one or more dimensions of AC, thus indicating incomplete ability to absorb external knowledge.

In the second phase, the levels of PAC/RAC were matched with the firm's stage of SM adoption. In the final phase, the transcripts were probed for antecedents of PAC and RAC using the integrative framework developed as guidance and looking also for emerging factors. Finally, the authors discussed results of the within-case analysis and addressed discrepancies by referring back to data, until an agreement was reached.

The cross case-analysis compared cases pairwise within groups and then across groups to identify consistent patterns between more advanced stages of SM adoption and levels of PAC/RAC. Finally, the research team worked to link technological and organizational antecedents to different levels of PAC/RAC. In this process, tables, graphs, and flow charts were used to facilitate analysis and comparisons (Miles et al., 2013).

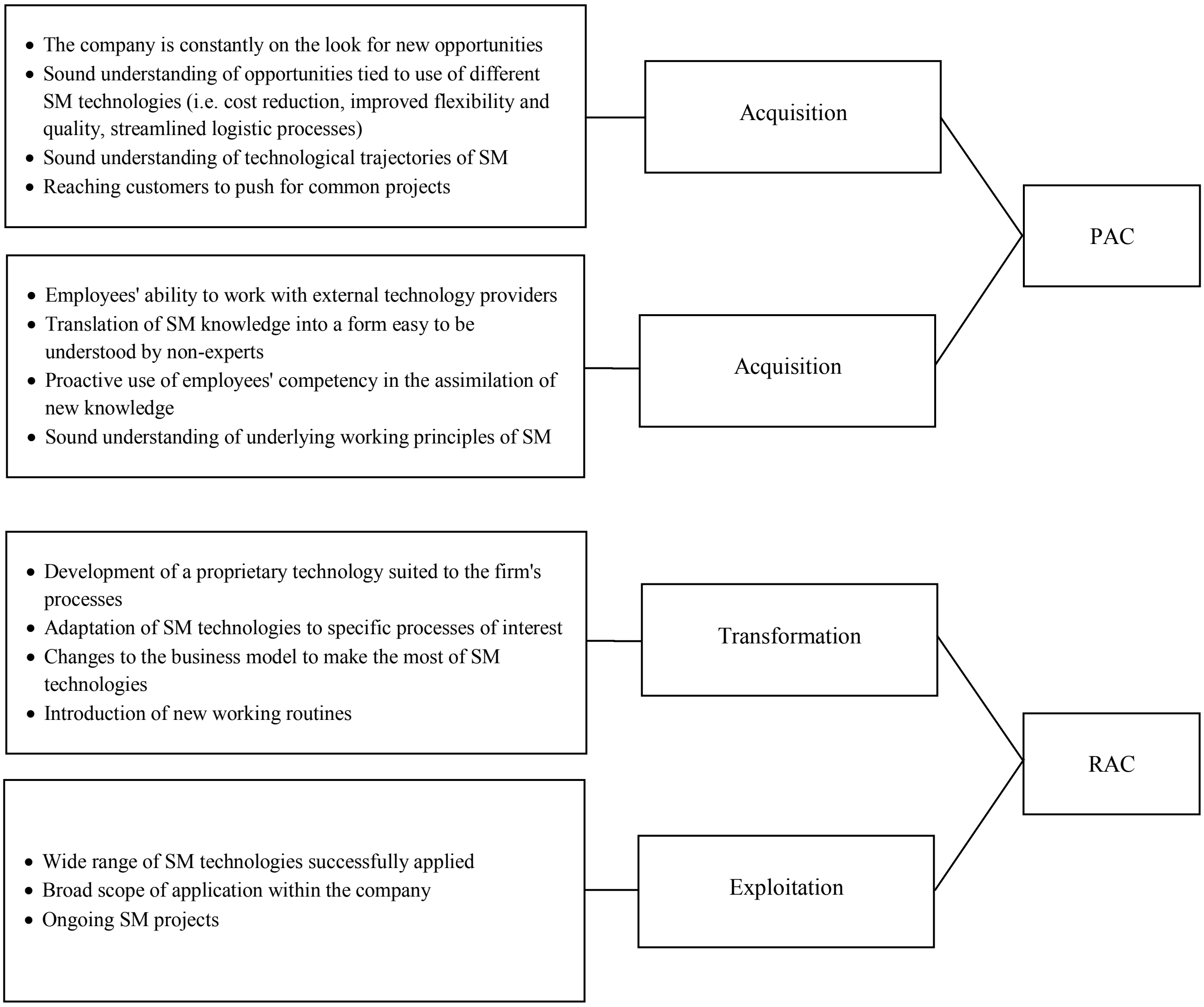

Figure 4: Indicators of AC

3.6 Findings

3.6.1 PAC, RAC and SM adoption

The first stage of the qualitative analysis aims at connecting firms' levels of PAC and RAC to progressively sophisticated capacities enabled by SM (Ancarani et al., 2019; Frank et al., 2019; Moeuf et al., 2018).

Table 6 suggests that the most advanced firms (frontrunners) consistently exhibit high levels of PAC *and* RAC. To illustrate, Frontrunner2 has built over the years a sound understanding of working principles of a wide range of SM technologies, extending from advanced robotics

Table 6: Firms' degree of PAC/RAC and stage of SM adoption

	Name	PAC		RAC	
		Low	High	Low	High
Frontrunners	Frontrunner1		X		X
	Frontrunner2		X		X
Laggards	Laggard1	X		X	
	Laggard2	X		X	

to simulation. As a result, the company has been among the first in its sector to detect the opportunity to use digital-twin technology to achieve real-time optimization of key parameters of its presses. At the same time, Frontrunner2 has progressively introduced a broad range of SM technologies, which have deeply modified its employees' working routines. In fact, over the years, shop-floor workers have gone from performing production tasks to supervising operations of totally automated production cells and analysing data collected from machines. Fully autonomous processes at Frontrunner2 include production scheduling, raw material picking and production. Further, the company is currently testing a system that leverages IoT, artificial intelligence and advanced robotics to automate its outbound logistics. To summarize, as a result of their high AC, frontrunners are able to interconnect diverse technologies with the aim to optimize and confer autonomy to their processes.

Conversely, laggards are characterized by low levels of PAC and RAC. Laggard1 for many years has neglected searching for opportunities offered by SM. Only recently, the firm has started considering SM in response to increasingly stringent industry standards that it could no longer meet with its existing equipment. Given the insufficient absorption of SM knowledge, Laggard1 has only been able to introduce advanced automation, which allows remotely monitoring production. Similarly, Laggard2 has been able to leverage on the expertise of its Production Manager to acquire a sound understanding of SM opportunities in the field of predictive maintenance occupational safety. However, the company’s narrow focus limits its comprehension of other SM technologies. Further, the firm has struggled to adapt SM technologies to its specific processes and, as a result, it has introduced only a limited range of technologies that are used to monitor processes.

In summary, our findings confirm the general theory of AC by suggesting that PAC and RAC are both critical in order for organizations to adopt SM (Zahra and George, 2002). Based on the evidence presented, the following proposition is suggested:

Proposition 1 - SM stage of adoption is an increasing function of the simultaneous development of PAC and RAC.

3.6.2 Antecedents of PAC

Table 7 summarizes organizational and technological antecedents that characterise low/high PAC firms. IT infrastructure endowment and the presence of an internal R&D department, which proxy previous knowledge, cannot discriminate among PAC levels. Similarly, most firms appear to have preliminarily identified strategic goals to be achieved with SM and have linked them to relevant technologies, irrespective of PAC level.

Table 7: Case results: Technological and organizational antecedents of PAC

Antecedents		Technological			Organizational				
PAC Level		Updated IT infrastructure	Employees' digital competencies	R&D activities	Identification of strategic goals and linked SM tech.	Leadership support	Culture of openness to external collaborations	Cross-functional project teams	Specific roles for SM
High PAC	Frontrunner1	High	High	Yes	High	High	High	Yes	Yes
	Frontrunner2	High	High	Yes	High	High	High	Yes	Yes
Low PAC	Laggard2	High	Medium	Yes	Medium	Low	Low	No	No
	Laggard1	Low	Low	No	Medium	Low	Low	No	No

Low: antecedent is absent

Medium: antecedent is present, yet not fully developed

High: antecedent is present and fully developed

Low PAC firms exhibit lack of leadership support for SM, resulting in insufficient resources to sustain the acquisition of SM knowledge. As stated by several informants, top managers need to be competent and aware of the potential benefits of SM (Horváth and Szabó, 2019) in order to pro-actively direct the organization towards the search of relevant knowledge (Majundar et al., 2021).

Unambiguous distinctive traits of firms with high PAC are represented by cross-functional teams, digital skills, a culture of openness to external collaborations and the presence of specific internal roles for SM. Digital competencies, which are linked by respondents to the cumulated experience with digitalization over time, assist firms in SM assimilation rather than acquisition, as remarked by Frontrunner2:*"Over the years we have introduced basic automation and have invested in a new Enterprise Resource Planning system and then in a Manufacturing Execution System. The skills* *that we have progressively acquired come in handy to understand working principles and evaluate benefits arising from the use of SM."*

An organizational culture that is open to external collaborations emerged as a crucial determinant of high PAC. In most cases, laggards' deliberate avoidance of external collaborations was rooted in top management fear of knowledge spillovers, which could undermine the competitive advantage generated by SM. For example, to minimize collaboration with external partners, Laggard1 acquired a company with expertise in advanced automation. However, avoidance of external collaborations led firms to confront unprecedented complexity challenging its expertise. In fact, the strategy of developing own SM solutions is especially daunting in light of the multiplicity of technological domain required (Benitez et al., 2020). As a result, manufacturing firms that deliberately avoid searching for SM partners might fall behind in terms of technological developments (Tumbas et al., 2018). Companies with high PAC evaluated spillover risks prior to establishing long-term partnership with technology providers but concluded that the advantages of the partnership outweighed disadvantages: *"In SM, developments are fast, and you need specific expertise that we do not possess. We recognize that collaborating with technology partners may result in the loss of part of our know-how. However, the alternative would be to fall behind on technology, which is worse."* (R&D Manager, Frontrunner2).

A distinctive feature of firms with high PAC is the scope of external collaborations, with diverse and multiple partners (e.g. technology providers, universities, start-ups) being selected depending on the exploitative or explorative nature of SM projects, as explained by the Chief Digital Officer (CDO) of Frontrunner1: *"We collaborate with an established technology supplier and a car manufacturer to co-develop an Additive Manufacturing technology, which is particularly suited to our processes. Since the additive business is about speed and flexibility, we are also working with a few start-ups, especially in finding new ways to interact with customers, to handle orders… We have also ongoing SM projects with universities, in fields in which the R&D component is especially relevant. "*

The creation of internal roles specific to SM, who are responsible for scanning the market in search for potentially valuable SM solutions and for establishing and supervising external collaborations, proves to be decisive. Further, the SM technical expertise of these boundary spanners supports both knowledge acquisition and assimilation. For instance, the CDO of Frontrunner1 acted as the champion for the additive manufacturing projects, selecting the technologies and partners and building up consensus around the technology inside the company.

Based on the evidence collected, we suggest the following propositions concerning the technological (Proposition 2a) and the organizational (Proposition 2b) antecedents of high PAC in the context of SM:

Proposition 2a - Employees' strong digital skills distinctively characterise firms with high PAC.

Proposition 2b - An organizational culture open to external collaborations and the appointment of specific roles for SM distinctively characterise firms with high PAC.

3.6.3 Antecedents of RAC

Table 8 summarizes findings concerning the relation between RAC and the organizational and technological antecedents.

The analysis of technological antecedents suggests that an updated IT infrastructure is not exclusive to high RAC firms. Conversely, close ex-ante scrutiny of potential technological compatibility issues distinguishes high PAC from low PAC firms. To illustrate, Laggard2 invested in IT infrastructure but purchased SM robots without running an adequate analysis to assess inter-operability, resulting in a strenuous and time-consuming transformation phase. "*Today, more than one year later, we are still working on interconnection. We have recently hit another roadblock. We discovered that the IP address of advanced robots that were purchased cannot be changed without a specific software. It is a fight!"* (Production Manager, Laggard2).

Table 8: Case results: Technological and organizational antecedents of RAC

Antecedents		Technological			Organizational						
RAC Level		Evaluation of technological. compatibility	Updated IT infrastructure	Employees' digital competences	Leadership support	Communication about I4.0 projects	Training	Cross functional project teams	Specific roles for I4.0	Operational planning for implementation	Agile organizational structure
High RAC	Frontrunner1	High	High	High	High	High	High	Yes	Yes	Yes	Yes
	Frontrunner2	High	High	High	High	High	High	Yes	Yes	Yes	No
Low RAC	Laggard2	Low	High	Medium	Low	Medium	Low	No	No	No	No
	Laggard1	Medium	Low	Low	Low	Low	Low	No	No	No	No

Low: antecedent is absent

Medium: antecedent is present, yet not fully developed

High: antecedent is present and fully developed

Companies with high RAC developed pilot projects to assess how to integrate SM into existing configurations, prior to scaling-up implementation. The R&D manager of Frontrunner2 described this process as a funnel, which allows firms to evaluate the potential of assimilated SM knowledge and leads to eventually retain only feasible technologies.

As expected, exploitation of SM knowledge is fostered by employees' digital skills (Kamble et al., 2018; Xia and Roper, 2008). In particular, firms with high RAC stress the need to build these competences on a continuous base: *"We undertook the first digitalization projects in 2006 and our personnel's digital competencies have evolved over time. So, introduction of SM technologies was perceived as a natural evolution."* (CEO, Frontrunner2).

Organizational factors are perceived by the respondents to be more critical for RAC than technological ones: *"Technological aspects in SM projects are somehow manageable. The biggest challenge is about the exploitation phase, when it really goes down to people's behaviour, when they really need to start using these solutions."* (CDO, Frontrunner1).

SM has a strong impact on human resources, as it calls workers to modify established routines (Hofmann and Rusch, 2017) or to acquire cross-disciplinary skills (Whysall et al., 2019). As confirmed by all high RAC firms, it is important to offer support to employees along two lines in order to manage this change. First, leadership must sustain the cultural transition to SM and provide a vision of the future (Flatten et al., 2015): *"The top manager must be absolutely convinced that what we are doing is a source of benefit for the company. Otherwise, the stubbornness to carry on hardly goes down to the production areas and everything becomes more complex and slower."* (CEO, Frontrunner2).

Next, top management must share information with subordinates on the goals of SM projects. Low RAC firms either miss sharing this information or adopt a top-down approach, which hinders workers from developing trust in the system and hampers exploitation, as Laggard2's Production Manager explained: *"When we introduced a new vision system to detect flawed parts, workers kept changing system settings to override it. It was a nightmare!"*.

Table 7 highlights other organizational antecedents that are distinctive of high RAC firms. In particular, these firms develop detailed operational plans for implementation of SM projects, which encompass the adaptation of existing technological systems and the support activities for human resources through training programs. In addition, steps for effective exploitation of SM knowledge are defined by cross-functional project teams coordinated by appointed specific SM roles: *"Prior to starting the implementation phase, we define steps and for each one we conduct a feasibility analysis. You need to evaluate impact of changes that will be made from different perspectives, so different kinds of expertise have to be involved."* (R&D manager, Frontrunner2).

"Besides considering technical issues tied to modifications to existing equipment, our project teams also evaluate potential skill gaps and plan the needed training activities." (CDO, Frontrunner1).

Findings suggest that lack of structural agility does not hinder RAC. However, some respondents acknowledge its importance, when they advocate a cultural change within their businesses: *"The real value added from digitization goes through the evolution of skills and corporate culture towards analysis, problem solving and control activities, with an emphasis on multi-disciplinarity and responsibility for common results."* (R&D manager, Frontrunner2).

Based on case evidence presented, the following propositions are suggested to identify prominent technological and organizational antecedents of RAC in the context of SM:

Proposition 3a – Employees' digital competencies distinctively characterise firms with high RAC.

Proposition 3b - Detailed operational plans for the introduction of SM, supported by the presence of specific coordinating roles and the provision of training to employees distinctively characterise firms with high RAC.

3.7 Discussion

This study has endeavoured to integrate the results of AC research into the SM context, and to apply comparative case analysis to generate propositions concerning the role of external knowledge absorption for SM adoption. Results suggest that both potential and realized AC are influential to achieve more advanced SM stages. Frontrunners in SM consistently exhibit the ability to pro-actively detect technological opportunities. Additionally, these firms leverage workers' experience and digital competencies to facilitate the assimilation of new knowledge. At the same time, frontrunners are characterised by structures and processes that support the adaption of SM to their activities. As a result of their high AC, frontrunners are able to interconnect diverse technologies to optimize and confer autonomy to their processes (Frank et al., 2019), thus laying the ground for sustained competitive advantage (Tortorella et al., 2020).

Next, findings point to the importance of both technological and organizational antecedents for the absorption of SM knowledge, thus confirming Volberda et al. (2010). Among technological factors, the bottleneck seems to be represented by weak digital skills rather than by inadequate technological infrastructure. Although digital skills have already been pinpointed as a necessary pre-requisite of the SM transformation (Mittal et al., 2018; Veile et al., 2019), our results show that they are relevant not only for the application of SM but also to direct the process of SM competence acquisition and assimilation. In this light, findings also highlight the importance for managers to strengthen internal competences by committing to training programs and by undertaking selective hiring.

Turning to organizational factors, a key driver of high PAC is represented by openness to collaborations. Unlike previous technological paradigm shifts (e.g. IT), SM is not a monolithic body of knowledge but rather an array of diverse but complementary technologies. Grasping and adapting these technologies to the firms' needs calls for the ability to create and manage a network of solution providers. This recommendation, which draws from AC research (Spithoven et al., 2010; Xia and Roper, 2008), has only very recently emerged in SM literature and has only partially trickled into firms' technology acquisition practices, as our case firms confirm. Building an SM innovation ecosystem is extremely valuable especially for small and medium enterprises, as a way to procure ready-made solutions but also to co-create solutions with technological partners (Benitez et al., 2020).

Equally important is the presence of boundary scanners with the role of helping resolve the conflict perceived among the previous well-established IT logic and the SM logic (Calvi et al., 2020; Tumbas et al., 2018). These roles, which emerge as central for knowledge acquisition and assimilation, need to be coupled with "implementers" in the transformation/exploitation phase, either acting as project managers or playing coordinating roles as part of the SM operational planning. The importance of supporting roles for the SM transformation has been so far an understudied research topic (Zheng et al., 2019). Our results call for future studies that explore how they can contribute to knowledge absorption and to the creation of the SM ecosystem.

In order to support RAC, organizations should also encourage communication by managers to employees and among employees, thereby laying the ground for rapid diffusion of the goals of SM projects and the alignment of required behaviours (Jansen et al., 2005). Further, communication should convey the vision of the SM transformation and create a new cultural identity inside the organization that fosters the acceptance of change (Flatten et al., 2015).

The emergence of a new technology paradigm calls organizations to update their knowledge base and may upturn the factors that drive successful knowledge absorption and application. In this perspective, our study has also sought to explore whether the theory of AC can adequately predict and explain the ability of firms to leverage external knowledge to reach higher level capacities enabled by SM. Using a theory elaboration approach, our findings suggests that the general architecture of AC suits the SM context and that AC is a good predictor of firms' ability to embrace the SM transformation. However, findings also point to factors that are only partially accounted for in the traditional AC literature and which may be central for SM. In particular, findings pinpoint the importance of operational plans for implementation of SM and the need to couple boundary scanning roles necessary to build PAC with "implementers" role that are functional to RAC. Finally, results suggest that SM, more than previous technological paradigms, requires companies to open up to collaborations. This extends also to small and medium enterprises, which must overcome their reluctance for fear of negative impacts and must start building their SM network. Conversely, we find little evidence of the relevance of organizational structural characteristics such as agility and of capabilities such as formalization (Jansen et al., 2005; Van den Bosch et al., 1999). These findings may depend on the fact that the case firms may not have yet reached a level of SM maturity that leads them to adapt their organizational system to their innovation strategy (Frank et al., 2019).

CHAPTER 4. Building absorptive capacity to progress in Smart Manufacturing

4.1 Purpose

The previous chapter has pointed at the existence of a link between firms' level of AC and the stage of SM adoption and has suggested that organizational factors play a pivotal role in facilitating the absorption of externally generated SM knowledge. This chapter aims at expanding these findings by exploring how AC supports progression in SM and how firms need to harness organizational factors to enable the absorption of increasingly complex SM knowledge. Specifically, managerial factors are analyzed, since they set the context for enhancing the potential to learn and then act on that knowledge (Bouguerra et al., 2021). To this end, evidence from twelve in-depth case studies of firms operating in the automotive supply chain and exhibiting different stages of SM adoption is used.

This chapter is adapted from: *"The role of absorptive capacity in the adoption of Smart Manufacturing "*[7].

4.2 Positioning of the research

Several manufacturing industries are currently undergoing a period of market turbulence and rapid technological change that requires keeping pace with the accelerating rate of innovation, while reducing costs and maintaining high quality standards (Kamble et al., 2020a). SM technologies are considered strategic to successfully navigate these challenges, as they promise to deliver significant improvements in operational and financial performance (Dalenogare et al., 2018; Lorenz et al., 2020; Tortorella et al., 2019; Tortorella et al., 2020). SM lies at the core of the Industry 4.0 revolution (Frank et al., 2019) and represents a building block of adaptable systems, which automatically adjust processes to allow for multiple types of products and changing conditions (Kagermann et al., 2013). Despite the strategic importance of SM, a fragmented adoption process is observed and many firms fail to advance in SM (Arcidiacono et al., 2019; Lin et al., 2018; Raj et al., 2020).

SM adoption has been conceptualized as a series of stages of growing complexity (Frank et al., 2019), which require the progressive addition and interconnection of multiple and complementary technologies (Culot et al., 2020; Dalenogare et al., 2018). Because of the rapid evolution of the digital landscape, transitioning to more complex SM stages calls organizations to continually adapt and transform (Sousa-Zomer et al., 2020). These features have important implications for the dynamics of the firm's knowledge base. In fact, in order to incorporate and exploit the potential

[7] Arcidiacono, F., Ancarani A., Di Mauro C., Schupp F., 2022. The role of absorptive capacity in the adoption of Smart Manufacturing. International Journal of Operations & Production Management 42(6): 773-796.

offered by multiple and fast advancing technologies, firms must possess the capacity to search and process new, specialist, and sometimes distant technological knowledge generated outside their boundaries (Culot et al., 2020; Ricci et al., 2021), and to integrate it with internal knowledge. Past innovation research has shown that this ability, known as AC (Cohen and Levinthal, 1990; Zahra and George, 2002), has been a key dynamic capability for the introduction of earlier breakthrough technologies (Gomez and Vargas, 2009; Lin, 2014; Zhang et al., 2018). The fast pace of evolution of SM technologies is expected to require an unprecedented pace of accumulation and integration of technological knowledge, therefore suggesting a critical influence of AC for SM adoption but also calling for research that throws light on how the ability to capture and transform SM-related external knowledge has to evolve to support incorporation of increasingly complex SM technologies. To date, few studies have investigated AC in the context of SM (Lorenz et al., 2020; Mahmood and Mubarik, 2020; Müller et al., 2021).

Past innovation research adopting the AC lens argues that knowledge accumulation and exploitation is supported by multiple antecedents. Among these, managerial antecedents, i.e. the capacity of managers to create, extend, or modify the knowledge base of an organization, have been pinpointed as crucial (Jansen et al., 2005). In fact, while an organization's prior knowledge is the root of its AC (Cohen and Levinthal, 1990), management sets the context for enhancing the potential to learn and then act on that knowledge (Bouguerra et al., 2021; Volberda et al., 2010). Key managerial antecedents to support knowledge absorption have been identified in combinative capabilities, i.e. ability to coordinate, integrate and socialize knowledge (Jansen et al., 2005), in management cognition (Flatten et al., 2015), and in individual knowledge development/sharing capabilities (Volberda et al., 2010). However, because SM research has predominantly placed emphasis on technological antecedents of SM (Frank et al., 2019), there is insufficient understanding on how managerial antecedents can contribute to shape the SM transformation (Horváth and Szabó, 2019). More in particular, the role and evolution of these capabilities in supporting SM knowledge acquisition and SM adoption is still an open research question. Further, a clear understanding and separation between capabilities that are critical at early SM stages and those that are key to progress to more complex SM stages is still missing. To fill these gaps, this study addresses two research questions:

R2c: How does absorptive capacity allow firms to progress to more advanced stages of Smart Manufacturing?

R2d: How do managerial antecedents support knowledge absorption at different stages of Smart Manufacturing?

Because the emphasis of the investigation is on "how" the ability to absorb SM-related knowledge evolves, the study follows an exploratory approach through multiple case studies (Eisenhardt, 1989; Yin, 1994). Twelve firms operating as part of the upstream automotive supply chain provide an appropriate setting for the study because SM is already the norm among vehicle manufacturers and Original Equipment Manufacturers (OEMs), while suppliers are under pressure to upgrade their technological competencies (Lin et al., 2018).

The study responds to ongoing calls in Operations Management literature for further research on dynamic capabilities that are relevant in the context of the digital transformation (Sousa-Zomer et al., 2020). In this perspective, it contributes by exploring how AC evolves to sustain firms' SM progression and by shedding light on how managerial capabilities support firms' AC. In doing so, findings provide guidance to manufacturing executives who are engaged in the SM transformation, by throwing light on crucial factors that must be developed or enhanced to support SM progression.

4.3 Background for the study

4.3.1 Smart Manufacturing

The fourth industrial revolution, also called Industry 4.0, envisions the widespread application of technologies related to digitalization, automation and connectivity in manufacturing contexts (Brettel et al., 2014; Kagermann et al., 2013). Although its key principles and enabling technologies are not entirely novel, Industry 4.0 is considered by many a new industrial paradigm in virtue of the unprecedented integration between physical objects and digital technologies (Dalenogare et al., 2018; Kagermann et al., 2013; Xu et al. 2018).

Within the Industry 4.0 paradigm, the use of advanced technologies in firms' internal production systems is commonly labelled SM (Frank et al., 2019). SM allows highly connected manufacturing systems both horizontally and vertically (Dalenogare et al., 2018; Xu et al. 2018). In turn, the enabled live information flow paves the way for autonomous operations that can be controlled and optimized in real time (Moeuf et al., 2018). Research consistently identifies SM as a potential source of competitive advantage, given its ability to generate improvements in productivity, time-to-market, flexibility, inventory and supply chain management (Delic and Eyers, 2020; Hofmann and Rüsch, 2017; Wamba et al., 2017).

SM is enabled by a broad array of front-end and base technologies (Frank et al., 2019). The former encompass endowments that directly support manufacturing activities, while the latter provide them with intelligence and connectivity. Prior research has shown that manufacturing firms think systemically with respect to SM adoption, since SM technologies are interdependent in their application (Culot et al., 2020; Eyers et al., 2018). Therefore, firms with advanced stages of SM adoption tend to use most of the SM technologies, rather than focus on a subset (Dalenogare et al., 2018). Frank et al. (2019) showed that SM adoption patterns are divided according to stable blocks of technologies, which exhibit growing degrees of complexity with respect to the modifications to production processes, plants' layout and employees' competencies they require. In particular, Frank et al. (2019) empirically defined three stages of SM adoption, with SM technologies at different stages playing complementary rather than substitutable roles. Firms at stage 1 (SM1) make wide use of consolidated SM technologies, which include vertical integration technologies such as Manufacturing Execution Systems (MES) and Enterprise Resource Planning (ERP). These enable the integration of information systems from different organizational layers to allow real-time information sharing (Jaskò et al., 2020). SM1 firms also adopt energy management solutions to guarantee efficiency of production (Tao et al., 2018) and traceability technologies for inbound and outbound material flows (Hofmann and Rüsch, 2017). Additionally, they leverage Cloud applications for remote data storage. Firms at Stage 2 (SM2) extensively use automation technologies and exploit IoT-collected data through virtualization technologies (e.g. artificial intelligence for predictive maintenance or quality) to support information-driven decision-making (Tao et al., 2018). Finally, Stage 3 (SM3) firms successfully integrate flexibility technologies such as additive manufacturing (Eyers et al. 2018; Li et al., 2018) and exploit Big Data and Analytics (Chen et al., 2015).

While the above classifications are important to build empirically validated definitions of SM adoption stages, it is important to identify the theoretical underpinnings for the mechanisms that allow firms to progress in SM. Recent contributions (Sailer et al., 2019; Sousa-Zomer et al., 2020; Warner and Wäger, 2019) have argued that the digital transformation involves continuously evolving target states and therefore requires adaptation to a constantly changing environment, not only in terms of technological endowments but also through organisational structures and processes. In this perspective, more than for past technological breakthroughs, dynamic capabilities, i.e. the capacity to reconfigure internal and external competences to address rapidly changing environments (Teece, 2007) are critical.

4.3.2 Absorptive capacity and its antecedents

Past research has shown that a key dynamic capability that supports technological innovation is represented by absorptive capacity (AC henceforth), i.e. a firm’s ability to recognize and assimilate new externally-generated knowledge, integrate external and internal knowledge and exploit it to develop new applications for commercial ends (Cohen and Levinthal, 1990; Zahra and George, 2002). AC has been proved critical for product innovation (Tsai et al., 2009) and for the adoption of several technologies including robotics and computer aided design (Gomez and Vargas, 2009), information systems (Zhang et al., 2018) and e-supply chain management systems (Lin, 2014).

AC is conceptualized as a four-dimensional process: acquisition, assimilation, transformation, and exploitation (Zahra and George, 2002). Acquisition and assimilation, which define firms' potential absorptive capacity (PAC), make organizations capable of searching and understanding new external knowledge. Transformation and exploitation, which define realized absorptive capacity (RAC), reflect firms' ability to combine external and internal know-how and exploit it to gain competitive advantage. Both PAC and RAC are necessary to benefit from externally generated knowledge (Zahra and George, 2002). In fact, firms concentrating exclusively on PAC are able to update their knowledge base but fail to reap its benefits. Conversely, organizations focusing on RAC may have a short-lived competitive edge, being prone to fall into a competence trap (Jansen et al., 2005; Volberda et al., 2010). The distinction PAC-RAC has been confirmed by several studies (Flatten et al., 2015; Jansen et al., 2005; Volberda et al., 2010) and indicators have been empirically validated (Camisòn and Forés, 2010; Noblet et al., 2011). PAC and RAC develop cumulatively over time and engender feedback loops between accumulated knowledge and organizations' future ability to absorb new external knowledge (Todorova and Durisin, 2007).

The concept of AC highlights that available external knowledge does not equally benefit all firms, because the ability to absorb is influenced by the firm's own actions (Cohen and Levinthal, 1990). In particular, while Cohen and Levinthal (1990) hold that AC mainly builds on the accumulated internal knowledge base, successive contributions have recognized the importance of finding the foundations of AC also in the ways a firm is organized and managed (Jansen et al., 2005; Lane et al., 2001). In their multi-level analysis of antecedents of AC, Volberda et al. (2010) highlight the relevance of micro-foundations of AC and in particular of managerial antecedents, which encompass the capacity of managers to create, extend, or modify the knowledge resource base of their organization (Adner and Helfat, 2003; Helfat and Martin, 2015). In particular, managerial antecedents may prove critical for the efficient acquisition and transformation of external knowledge (Lenox and King, 2004), especially in industries and settings characterised by rapid change (Helfat and Martin, 2015; Helfat and Raubitschek, 2018) and whenever firms must be in "continuous adjustment mode" (Sousa-Zomer et al., 2020).

Building on dynamic capabilities research, Volberda et al. (2010) identify three classes of managerial antecedents: combinative capabilities (CC), management cognition/dominant logic (MC) and knowledge development/sharing capabilities (KDC). Starting from an initial set of core AC articles (Jansen et al., 2005; Volberda et al., 2010; Zahra and George, 2002), we identified specific managerial antecedents relevant for AC through a snowballing literature search strategy. In particular, backward snowballing and forward snowballing was performed until snowballing iterations failed to reveal articles not previously included (Table 9).

Combinative capabilities (CC) (Kogut and Zander, 1992): include adaptive and integrative system-level capacities that enable integration of new technologies with existing configurations (Robertson et al., 2012). Additionally, CC include coordination and socialization capabilities (Jansen et al., 2005). The former consist of cross-functional interfaces, job rotation and participatory decision-making. The latter facilitate interpretation of new knowledge and enable peer-to-peer interactions through informal networks and, therefore, foster AC by conveying the value of new practices throughout the organization (Bouguerra et al., 2021; Jansen et al., 2005).

Management cognition/dominant logic (MC) (Dijksterhuis et al. 1999): influences AC through leadership vision (Flatten et al., 2015) and management's ability to offer the needed resources to support subordinates in the process of change and set the organization to act in learning mode (Li et al., 2018). Further, MC impacts AC by supporting new organizational forms (Volberda et al., 2010) and through information provision by managers (Lenox and King, 2004).

Individual knowledge development/sharing capabilities (KDC) manifest through the character and distribution of expertise within the organization, such as the assignment of gatekeeping or boundary-spanning roles (Volberda 1996). Next, KDC translate into organizations characterised by "porous boundaries", which are defined by interactions with technology sources (Spithoven et al., 2010) and by the network of external technological collaborations. Though AC has also been pinpointed as a moderator between external collaborative networks and innovation (Tsai et al., 2009), research highlights that collaborative networks foster AC by increasing the opportunity for learning and by providing access to new resources and capabilities (Fosfuri and Tribò, 2008; Laursen and Salter, 2006; Omidvar et al., 2017). The impact of the breadth of the collaboration network on AC is generally viewed as positive, as a variety of external channels may lead to overcome local search biases (de Araújo Burcharth et al., 2015). However, for knowledge-intensive digital technologies, Lorenz et al. (2020) suggest that firms should rather establish strong ties with few external knowledge partners, rather than weak relations with many. Finally, KDC occur through training and employees' skills development/transformation (Lane et al., 2001; Wang et al., 2018; Xia and Roper, 2008).

Table 9: Main managerial antecedents of AC

Categories		Antecedents of AC
Managerial antecedents (Volberda et al., 2010)	Combinative capabilities (CC)	Adaptive and integrative capacities (Garrety et al., 2004; Robertson et al., 2012)
		Coordination capabilities (i.e. cross-functional teams, job rotation, participatory decision-making) (Bouguerra et al., 2021; Jansen et al., 2005)
		Socialization capabilities (Bouguerra et al., 2021; Jansen et al., 2005)
	Management cognition/ dominant logic (MC)	Leadership (Flatten et al., 2015)
		Resources to support subordinates' learning (Li et al., 2018)
		Information provision by managers (Lenox and King, 2004)
	Individual knowledge development/ sharing (KDC)	Gatekeepers or boundary spanners (Cohen and Levinthal, 1990; Volberda, 1996)
		Interaction with technology intermediaries (Spithoven et al., 2010)
		Openness to external collaborations (de Araújo Burcharth et al., 2015; Fosfuri and Tribò, 2008; Laursen and Salter, 2006; Omidvar et al., 2017)
		Training and employees' skills development/transformation capabilities (Lane et al., 2001; Xia and Roper, 2008; Wang et al., 2018)

In the remainder of the chapter, we follow Volberda et al. (2010) by referring to the above managerial capabilities as managerial antecedents of AC.

4.3.3 The role of AC for SM

In the wider context of Industry 4.0, research encompassing the AC lens is still in its infancy. The relevance of AC has been pinpointed by showing that it enables ambidextrous innovation strategies (Mahmood et al., 2020; Müller et al., 2021). The relation with technology adoption has been explored by Lorenz et al. (2020), who find a positive impact of depth but not of breadth of external knowledge search for the adoption of specific digital technologies.

There is currently a lack of formal understanding of whether and how external knowledge search and acquisition can support different stages of SM. Advancement in SM can be interpreted as a knowledge accumulation process, whereby each stage of base and front-end SM technologies requires acquiring new specialist knowledge from outside the firms' boundaries and integrating it with the internal knowledge base. As argued in Section 4.3.1, the digital transformation calls organizations to exert an unprecedented adaptation to a constantly shifting technological target state (Sousa-Zomer et al., 2020; Warner and Wäger, 2019), thereby hinting at the criticality of AC as a dynamic capability supporting SM adoption. In particular, prospective adopters could leverage their PAC to recognize the potential of new, diverse SM knowledge in an evolving technological field (Culot et al., 2020) and to understand the information obtained, which may be distant from their existing knowledge base (Robertson et al., 2012). Further, internal processes need to be redesigned and streamlined (Hofmann and Rüsch, 2017) and compatibility issues with legacy infrastructures have to be tackled in order to successfully integrate new blocks of SM technologies. Finally, incorporation of more advanced SM requires substantial changes to work organization, such as in the case of flexibility technologies (Eyers et al., 2018; Frank et al., 2019). To this end, RAC can support the successful transformation and exploitation of new technologies.

As firms advance in SM, external knowledge typically becomes more complex and distant. For instance, Dalenogare et al. (2018) highlight that manufacturers have difficulties in understanding the potential of Big Data and Analytics. This observation hints that, in order to progress in SM, firms may need to dynamically increase their knowledge absorption capacity. The process can be described as being characterised by iterative cycles (Todorova and Durisin, 2007), as illustrated in Figure 5. This conceptualization views AC growth and SM progression as intertwined processes, in which SM-related knowledge at any point in time lays the ground for the future development of the capabilities to absorb more complex SM knowledge.

If AC plays a positive role for SM, it is important to throw light on how managerial antecedents need to evolve to support more mature stages of SM. Empirical evidence supports the relevancy of managerial antecedents for digitalization processes, for instance by highlighting the importance of leadership support to the digital strategy (Kane et al., 2016), of SM information diffusion within the organizations (Warner and Wäger, 2019), and of capabilities for project management (Sony and Naik, 2020). However, there is still a lack of understanding of how managerial antecedents supports SM adoption in terms of knowledge acquisition and transformation. The following sections present an exploratory study of how AC and managerial antecedents support firms in moving from baseline stages (SM1) to advanced stages (SM3).

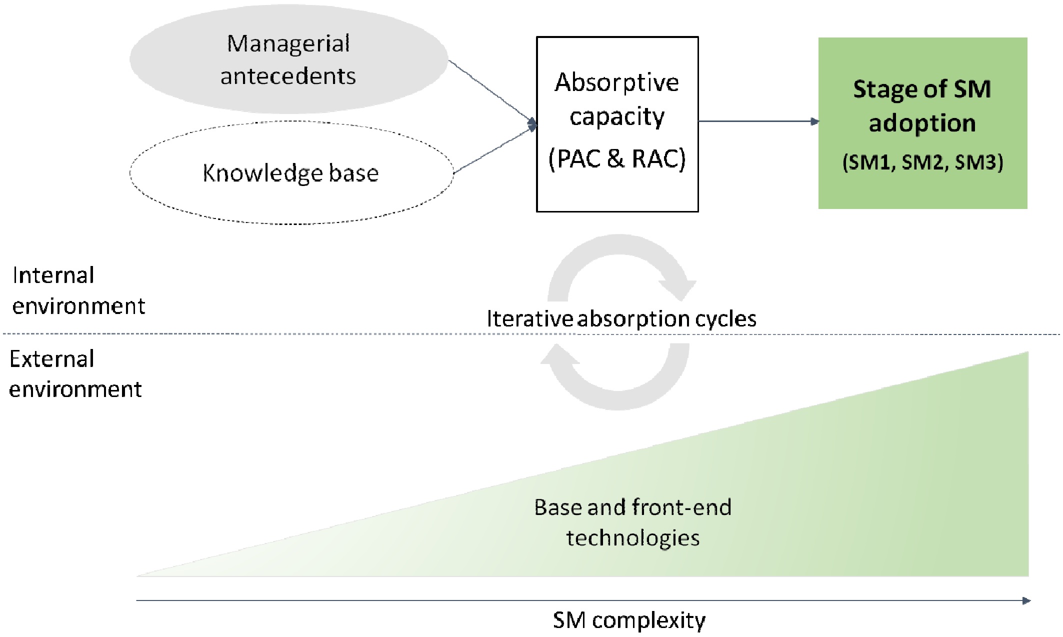

Figure 5: An AC perspective on SM adoption

4.4 Research Methods

Because the goals of the study are to understand whether and how AC allows firms to progress to more advanced stages of SM and how managerial antecedents support AC in this evolution, this research follows an exploratory approach through multiple case studies (Bluhm et al., 2011; Eisenhardt, 1989; Yin, 1994). The novelty of the research topic further supports the choice of the methodology, as case studies are valuable to generate new insights into emerging phenomena (Gioia et al., 2013). Since AC is generally regarded as a firm-level construct (Cohen and Levinthal, 1990; Todorova and Durisin, 2007), the firm was selected as the unit of analysis. In retrieving case firms' information multiple sources were used, including semi-structured interviews, archival data, and field notes. Triangulation was used to enhance construct validity (Barrat et al., 2011).

4.4.1 Case selection

The automotive industry was selected as the setting for this research. In fact, automotive is making larger investments in SM than any other sector in manufacturing (Kamble et al., 2020a). Therefore, respondents from the industry are expected to be aware of the opportunities and challenges tied to SM. Additionally, there is still incomplete alignment of supply chain partners as far as advancement in SM is concerned (Lin et al., 2018), therefore making the investigation of SM adoption and of its antecedents valuable (Kamble et al., 2020b). Northern Italy was chosen as the geographical context for the analysis, given its recognized specialization in metal work and automotive component manufacturing and because it houses relevant players within the European automotive supply chain.

The research team worked together with a technology expert from industry to critically discuss the classification of SM adoption stages proposed by Frank et al. (2019). The expert confirmed the appropriateness of conceptualizing three SM stages and contributed to contextualize the relevant technologies to the automotive supply chain. In particular, since automotive suppliers often approach SM with an initial focus on automation, which is considered a low-complexity means to respond to cost pressures in the industry (Arcidiacono et al., 2019; Dalenogare et al., 2018; Horváth and Szabó, 2019), Frank et al. (2019) classification was slightly modified by including in SM1 basic front-end automation technologies, such as automatic nonconformity identification and industrial robots. SM2 includes full vertical integration and traceability and energy management technologies. Additionally, firms at SM2 leverage IoT and Big Data to interconnect their equipment and collect production data, which however are not systematically analysed. Finally, SM3 firms have successfully integrated a broad range of front-end technologies, including virtualization and flexibility technologies, and master base technologies to achieve fully connected production systems and to expose underlying trends in production data.

Case selection followed the theoretical sampling principle (Eisenhardt and Graebner, 2007). Based on the three SM stages defined, eleven experts at a large OEM (supply managers, buyers and technology experts) were asked to identify among their first-tier suppliers replicated cases (Yin, 1994) of SM3, and contrary replicated cases of SM1 firms. Additional cases of SM2 firms were selected to provide a more varied empirical evidence. Suppliers that had not implemented any form of SM were not considered for the study. Experts possessed an in-depth knowledge of suppliers' SM technological endowments, as they were regularly involved in suppliers' improvement programs. Additionally, they were asked to motivate their choices by discussing SM initiatives implemented and planned by suppliers and by sharing relevant archival data with the research team, including reports and presentations (Yin, 1994). Experts identified 25 potential case firms, whose CEOs were contacted and invited to the study. Twelve firms agreed to participate. These organizations are medium and large sized and belong to different industrial sectors (Table 10), which enhances generalizability of findings (Eisenhardt and Graebner, 2007; Voss et al., 2002).

4.4.2 Field data collection and interviews

Data collection took place between February and May 2019. The researchers spent one or two full days at firms' sites during which they carried out field tours of each firm’s SM lead plant and conducted multiple interviews. The field visits, which lasted about two hours and were led by the plant manager and a technology manager, provided a robust understanding of SM technologies adopted at each site (Table 10) and allowed cross-validating the initial classification of case firms.

Observations confirmed that companies exhibited homogeneous blocks of technologies according to their SM stage and that technologies pertaining to different stages were perceived to be complementary and augmentative rather than substitutable. Field notes were used as input for the first round of interviews and the final case reports. Interviews were conducted according to a semi-structured protocol - available in Appendix (Interview protocol) - probing firms' AC and managerial antecedents. The protocol was built on previous AC studies (Camisón and Forés, 2010; Noblet et al., 2011) and managerial antecedents emerging from the literature review (Table 9). Emerging factors that may have not been included in previous studies were noted.

A total of 37 in-depth interviews were carried out with at least two respondents per firm (Miller et al.,1997). All respondents were explicitly identified as SM experts by the CEO and had an influential role in the adoption of SM. Interviews were typically led by one researcher, while two other members of the research team took notes or asked additional questions. Conversations lasted 60 to 90 minutes, were tape recorded and transcribed (Mero-Jaffe, 2011). Field notes, interviews' transcripts and additional archival data supported the preparation of case study reports. Documents for each case were then organized into a database, which was reviewed by companies' informants to ensure reliability of data (Mero-Jaffe, 2011; Yin, 1994).

Table 10: Overview of case companies

	Name (Size - no. of employees)	Industry sector (Production processes)	No. of informants (Informants' job titles)	Base technologies	Front-end technologies (a. automation; b. vertical integration; c. energy management; d. traceability; e. virtualization; f. flexibility)
SM3	CoilsCo (Large-6500)	Manufacture of basic metals (Cold and hot rolling)	3 (Plant Manager, R&D Manager, Quality Manager)	○ Cloud ○ IoT ○ Big Data ○ Analytics	a. Automated nonconformities identification, industrial robots b. PLCs + sensors + actuators, SCADA, MES, ERP d. Traceability of raw materials/final products e. AI for predictive quality f. Additive manufacturing (only for spares)
	PlasticCo (Medium-180)	Manufacture of plastic products (Plastic injection molding)	3 (CEO, R&D Manager, Quality Manager)	○ Cloud ○ IoT ○ Big Data ○ Analytics	a. Automated nonconformities identification, industrial robots, M2M communication b. PLCs + sensors + actuators, SCADA, MES, ERP d. Traceability of raw materials/final products e. AI for predictive quality f. Additive manufacturing (only for spares)
	SinterCo (Large-6600)	Manufacture of fabricated metal products (Sintering)	4 (CEO, CDO, Quality Manager, Production Manager)	○ Cloud ○ IoT ○ Big Data ○ Analytics	a. Automated nonconformities identification, industrial robots, M2M communication b. PLCs + sensors + actuators, SCADA, MES, ERP c. Energy monitoring d. Traceability of raw materials/final products e. AI for maintenance f. Additive manufacturing
SM2	StampingCo1 (Large-460)	Manufacture of fabricated metal products (Metal forming)	2 (CEO, Production Manager)	○ Cloud ○ IoT ○ Big Data	a. Automated nonconformities identification, industrial robots b. PLCs + sensors + actuators, SCADA, MES, ERP c. Energy management d. Traceability of final products
	WiresCo1 (Medium-100)	Manufacture of fabricated metal products (Wire drawing)	2 (CEO, Quality & Production Manager)	○ Cloud ○ IoT ○ Big Data	a. Industrial robots b. PLCs + sensors + actuators, SCADA, MES, ERP c. Energy management d. Traceability of raw materials/final products
	WiresCo2 (Large-1400)	Manufacture of fabricated metal products (Wire drawing)	2 (CEO, Production Manager)	○ Cloud ○ IoT ○ Big Data	a. Automated nonconformities identification, industrial robots b. PLCs + sensors + actuators, SCADA, MES, ERP c. Energy management
SM1	CastingCo1 (Large-600)	Manufacture of basic metals (Iron casting)	3 (CEO, CDO, Sales Manager)	○ Cloud	a. Industrial robots b. PLCs + sensors + actuators, ERP
	CastingCo2 (Medium-200)	Manufacture of basic metals (Aluminum die casting)	3 (Quality Manager, Production Manager, Sales Manager)	○ Cloud	a. Automated nonconformities identification, industrial robots b. PLCs + sensors + actuators, ERP
	GearsCo (Large-550)	Manufacture of gears (Gear machining)	4 (COO, Quality Manager, Production Manager, Purchasing Manager)	○ Cloud	a. Automated nonconformities identification, industrial robots b. PLCs + sensors + actuators, SCADA
	RubberCo (Large-600)	Manufacture of rubber products (Compression molding)	3 (Plant Manager, R&D Manager, Quality Manager)	○ Cloud	a. Automated nonconformities identification, industrial robots b. PLCs + sensors + actuators, ERP
	StampingCo2 (Medium - 60)	Manufacture of fabricated metal products (Metal forming)	2 (CEO, Quality Manager)	○ Cloud	a. Automated nonconformities identification, industrial robots b. PLCs + sensors + actuators, ERP
	StampingCo3 (Medium-240)	Manufacture of fabricated metal products (Metal forming)	3 (HR & IT Manager, Quality Manager, Sales Manager)	○ Cloud	a. Automated nonconformities identification, industrial robots b. PLCs + sensors + actuators, ERP

4.4.3 Within-case and cross-case analysis

The research team familiarized with case reports and had several meetings to discuss and compare cases (Miles et al., 2013). Two authors were mainly responsible for the coding. In particular, the two researchers independently analysed the material for each case and multiple peer debriefings were held along the process to compare results. Discrepancies were addressed by referring back to transcripts and case reports, until an agreement was reached (Gioia et al., 2013).

For the within-case analysis, views and comments expressed by informants in the transcripts were manually identified and labelled with first-order indicators. Indicators were allowed to emerge until the analysis failed to reveal new ones. Next, indicators were organised into higher-level (second-order) concepts. At this stage, AC and SM literatures were incorporated to support the definition of theoretical themes related to firms' AC (Camisón and Forés, 2010; Noblet et al., 2011) and its managerial antecedents (Volberda et al., 2010) and to provide additional source of validation (Eisenhardt et al., 1989; Su et al., 2014). A coding table for one of the case firms that exemplifies the process followed is provided in Appendix (Table A).

For the cross-case analysis, the first phase involved comparison of coding tables across the case studies, which allowed identifying common second-order concepts relating to firms' PAC/RAC. These were grouped according to six theoretical themes (Figure 6).

Next, in order to facilitate interpretation of cross-case differences and assist in establishing a link between AC and SM stages, in analogy with the approach followed by Su et al. (2014) a table was created to summarize for each firm the second-order concepts relating to PAC and RAC (Appendix - Table B). Based on this table, three of the researchers were asked to independently rate firms' PAC and RAC as high, medium or low. Inter-rater reliability was calculated by means of Fleiss' kappa, whose value (0.88) suggests substantial agreement (Fleiss, 1971). At this stage, in order to answer the first research question, cases were compared pairwise within and across SM stages to identify consistent patterns linking firms' degree of PAC/RAC and stages of SM adoption.

Finally, to answer the second research question, cases were compared and contrasted to assess which managerial antecedents supported different degrees of AC (Appendix - Table C and Table D). In this process, tables, graphs and flow charts were used to facilitate analysis and comparisons (Miles et al., 2013). A second round of meetings was held during 2020 with some of the case firms to clarify why some of the managerial antecedents were associated to specific SM stages. Respondents' feedback and evidence from the second round of interviews were used to refine findings.

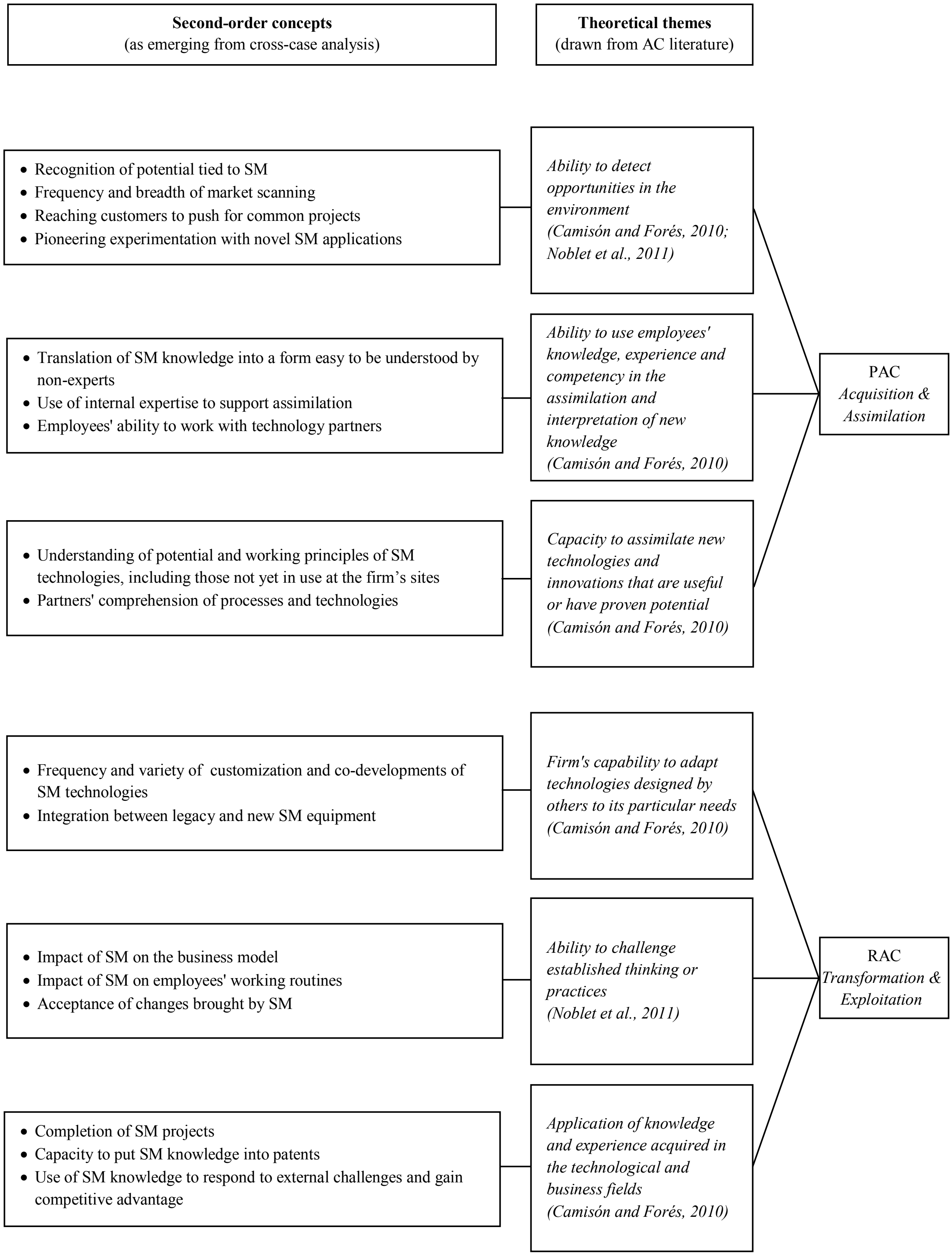

Figure 6: PAC/RAC: second-order concepts and theoretical themes

4.5 Findings

4.5.1 PAC, RAC and stage of SM adoption

The qualitative cross-case analysis was used to explore how the degree of PAC and RAC is related to the SM stage. Table 11 summarizes results using a contingency table, which suggests that advancement in SM is associated with higher PAC and RAC.

More specifically, SM1 firms are characterized by low degrees of either PAC or RAC. Low PAC firms do not perform regular market scanning and search for externally generated knowledge is prompted by market pressures. In the case of RubberCo, for many years the company failed to recognize opportunities offered by SM and, only recently, it has introduced new industrial robots and upgraded vision systems to meet the targets imposed by its customers. Additionally, SM1 firms have a basic understanding of working principles of SM, which is limited to technologies already in use at firms' sites, while analytics and virtualization technologies are often regarded with distrust. Because of low RAC, SM1 firms purchase only standard SM solutions available in the market and never customize. Similarly, low RAC hinders progress to higher SM stages because integration between legacy and new equipment is often challenging. As an example, CastingCo1 acquired industrial robots to be retrofitted on an existing production line. However, over one year was spent solving technology compatibility issues. Further, low RAC is manifest in challenges to modify workers' routines, because of workers' resistance to change, and explains why SM1 firms have opted to automate tasks previously performed by shop-floor workers. The CEO of CastingCo2 reports: *"When we introduced a new vision system to detect flawed parts, workers did not trust it and kept changing system settings to override it. It was a nightmare!"*.

SM2 firms exhibit higher levels of PAC and RAC. While they perform regular market scanning, the search focus is narrow, as these firms are mainly interested in automation and vertical integration technologies. Typically, in order to assimilate technological knowledge and envision applications, SM2 rely on the digital expertise of few organizational members. To illustrate, the Production Manager of WiresCo1 pointed out: *"I have a background in mechatronics, and I have a personal connection with a firm operating in that sector. Together we came up with the idea of using automation to reduce setup times of our machines"*.

However, understanding of working principles and potential of SM goes beyond technologies currently in use. To exemplify, WiresCo2 exhibited an in-depth knowledge of traceability technologies and of how they might eventually support operations.

Table 11: PAC/RAC and stage of SM adoption: contingency table

Stage of SM adoption	PAC: Low	PAC: Medium	PAC: High
SM3			• CoilsCo • PlasticCo • SinterCo
SM2		• StampingCo1 • WiresCo1 • WiresCo2	
SM1	• CastingCo1 • CastingCo2 • RubberCo • StampingCo2 • StampingCo3	• GearsCo	

Stage of SM adoption	RAC: Low	RAC: Medium	RAC: High
SM3			• CoilsCo • PlasticCo • SinterCo
SM2		• StampingCo1 • WiresCo1 • WiresCo2	
SM1	• CastingCo1 • CastingCo2 • GearsCo • RubberCo • StampingCo3	• StampingCo2	

SM2 firms customize SM solutions to their needs, as in the case of WiresCo2, which co-developed industrial robots suited to a specific application together with a technology partner. However, co-developed projects do not emerge as part of a systematic collaborative approach to SM innovation. Medium RAC supports SM2 adoption also thanks to their ability to smoothly integrate legacy and new equipment. Additionally, despite initial difficulties, modifications to work routines have been successful thanks to employees' change acceptance, as pointed out by the CEO of WiresCo2: *"We assigned our best shop-floor workers to the new industrial robots. Despite that, they initially struggled as they had to abandon well-known routines and learn everything from scratch. Today, however, they master this type of automation and this keeps us ahead of competitors"*.
Findings also highlight that in order for firms to progress from SM1 to SM2, both components of AC need to be equally developed, as exemplified by GearsCo and StampingCo2. GearsCo leveraged its Chief Operations Officer's wide expertise to identify SM opportunities for predictive maintenance and occupational safety. However, low RAC hindered the integration of SM technologies in its processes and currently it exploits only base SM1 solutions. Conversely, StampingCo2 was classified as medium RAC, having developed several own solutions in the field of automation. However, the company's sole focus on automation has limited its comprehension of other technologies (low PAC), thus hindering progress to SM2.
SM3 firms consistently exhibit high PAC and RAC. Concerning PAC, they perform market scanning for new technologies on a regular and broad base. Next, SM3 is also associated with firms' pioneering experimentation with novel SM applications. To illustrate, PlasticCo has been among the first in its sector to detect the potential of combining Cloud, IoT and Big Data to monitor the status of its presses, as the R&D manager explained: *"Digital twins are already in use in aerospace but are a novel concept in our sector. Nothing suitable for our applications is currently on the market, but we have a concept in mind"*.
Additionally, SM expertise is distributed across several managerial roles and functional competencies are actively combined to envision SM applications in different areas, including production, quality and logistics. Finally, comprehensive knowledge of the entire spectrum of SM technologies proves the capability of these firms to assimilate external knowledge.
Concurrently, high RAC enables multiple customizations of SM technologies to devise solutions tailored to their specific needs. For example, SinterCo co-developed an AM technology with a specialist supplier. Additionally, high RAC has assisted SM3 firms in introducing significant changes in employees' work routines. In the words of CoilsCo's R&D manager: *"Our shop-floor workers have moved from performing repetitive production tasks to supervising operations of*

totally automated production cells and taking autonomous decisions, based on insights obtained from real-time data".

High RAC also facilitates use of knowledge acquired to respond to external challenges and exploit SM to gain competitive advantage. For illustration, SinterCo has received preferred supplier status by several customers, due to its ability to stay at the technological edge. PlasticCo recognized SM as strategic to achieve greater flexibility, lower production costs, and higher quality. Similarly, CoilsCo stated: *"These investments have enhanced our competitiveness amid harsh market conditions. We have constantly been growing by 2-3% yearly."*

4.5.2 The role of managerial antecedents in the transition from SM1 to SM2

In this section and the following one, we explore how case firms leverage managerial antecedents (CC, MC, KDC) to support their PAC/RAC and achieve higher stages of SM. CC supported RAC in the transition from SM1 to SM2, in the form of adaptive and integrative capacities (Robertson et al., 2012), which were developed to solve compatibility issues between legacy technologies and new SM equipment, thus facilitating knowledge transformation. Specifically, routines were developed to evaluate technological compatibility, as explained by the production manager of WiresCo1: *"We have created a database which contains all requirements that need to be met to connect old and new equipment. Prior to starting any new project, we discuss them with the technology providers, so that when the new equipment comes in, it is just plug and play"*.

Concerning MC, with respect to SM1, SM2 firms have defined a clear strategic goal to be achieved through SM adoption. Clarity of goals orients firms' search for SM technologies, thus enabling higher PAC. MC also sustains RAC through the management of change acceptance. Specifically, the leadership sustained the transition to SM by conveying a vision of the technological future (Flatten et al., 2015), as stated by the CEO of WiresCo2: *"The top manager must be absolutely convinced that transformations entailed by SM are a source of benefit for the company. Otherwise, the willingness to carry on in the transformation process hardly trickles down to the production areas and everything becomes more complex and slower"*.

Additionally, prior to starting implementation, SM2 firms created a climate of trust by sharing information about the goals of each SM project (Lenox and King, 2004): *"We took pains at explaining that the MES was not a system aimed at monitoring employees' performance, but rather a tool to detect and solve problems. Thus, we were able to foster its acceptance when we actually introduced it" (*CEO of WiresCo1).

With respect to SM1, firms in SM2 possess KDC that enable them to achieve higher PAC. In particular, in order to facilitate acquisition of external SM knowledge, these firms regularly interact with technology providers (Spithoven et al., 2010), by assigning boundary spanning roles to Production Managers. Further, SM2 firms strengthen their PAC through long-term collaborations with selected technology providers, which orient them towards SM applications aligned with their strategic goals (de Araújo Burcharth et al., 2015; Laursen and Salter, 2006): *"In SM, you need technological expertise that we do not possess. It is not our core business. We recognize that by pursuing these collaborations we may risk part of our know-how. Yet, the alternative would be to remain isolated with no access to external expertise, which is certainly worse"* (CEO of WiresCo2). Conversely, SM1 firms shun external collaborations for fear of knowledge spill-overs. For example, StampingCo2 acquired a company with expertise in advanced automation to develop its own solutions. A similar solo strategy was undertaken by RubberCo. In both cases, firms confronted unprecedented complexity challenging their core expertise and fell behind in terms of technological developments.

4.5.3 The role of managerial antecedents in the transition from SM2 to SM3

Firms exploit CC to further enhance their RAC and transition from SM2 to SM3. In particular, SM3 managers use detailed operational plans for SM projects, which include evaluation of and provision for technological compatibility issues and the identification of employees' skill gaps. For the definition and monitoring of the implementation of these plans, SM3 firms rely on cross-functional project teams (Bouguerra et al., 2021; Jansen et al., 2005), which are coordinated by project managers under the direct supervision of R&D managers and CDOs. The R&D manager of CoilsCo explained: *"You need to evaluate impact of changes that will be made from different perspectives. The mere technical perspective has to be associated with consideration of the implications for human resources and new skills needed for the transition. So different kinds of expertise have to be involved".*

As for MC, the high PAC that characterizes SM3 firms is activated by the fact that leadership concurrently pursues multiple strategic goals, which require a wide range of SM technologies and calls for market scanning with a broad focus. According to PlasticCo's R&D Manager: *"Besides initiatives that enhance productivity of our lines, our roadmap includes a quality management project, multiple initiatives to automate our inbound and outbound logistics to improve delivery, and the use of AM to enhance our flexibility".*

Concerning KDC's influence on PAC, a key capability of SM3 firms manifests in the breadth and variety of their SM collaborations (de Araújo Burcharth et al., 2015; Laursen and Salter, 2006; Spithoven et al., 2010). All SM3 firms simultaneously pursue multiple and diverse partnerships (e.g. technology providers, customers, universities, start-ups), which are selected depending on the exploitative or explorative nature of SM projects: *"Concerning more mature production technologies, we mainly collaborate with traditional technology partners. We currently work with some start-ups, especially in the field of Analytics for quality predictive purposes… We have also ongoing SM projects with universities, in fields where R&D is especially relevant"* (CDO of SinterCo).

This broad and diversified network not only allows SM3 firms to acquire knowledge on cutting-edge applications but also to successfully co-develop SM solutions tailored to their needs, thereby increasing RAC. Given the importance of SM solutions co-development, SM3 firms assign responsibility for market scanning and for managing external collaborations to R&D managers and Chief Digital Officers (CDOs). For instance, the R&D manager of CoilsCo championed the additive manufacturing projects, selecting technologies and partners and building up consensus inside the company. In the transition SM2-SM3, KDC sustains RAC also by facilitating digital competence upgrading. In fact, SM3 firms exhibit training competencies and adopt innovative training methods (Lane et al., 2001): *"To generate value out of real-time production data, we needed our shop-floor workers to become agile problem-solvers. To do so, we have created an app that they use on their mobile devices that offers trainings customized to their needs and current skill set"* (CDO of SinterCo).

Additionally, to support a widespread application of SM across different functions, SM3 firms adopt acculturation practices meant to provide senior managers with competences in SM and in managing non-traditional technology partners. For SinterCo, this translated into regular visits to an innovation incubator: *"We went there to learn how to work with startups. Not really to find a supplier, but to understand how they approach problems, how they solve problems..."*

Figure 7 summarizes results of the analysis by highlighting that progression in SM needs to go alongside the increase in the capacity to absorb external technological knowledge. Further, it highlights which managerial antecedents defined by CC, MC and KDC are crucial for the firm's ability to expand its capacity for knowledge absorption. Specifically, results pinpoint that CC are consistently relevant for knowledge transformation and exploitation processes. MC supports both PAC and RAC by respectively orienting search for SM knowledge and by fostering change acceptance. Finally, KDC sustain PAC and RAC mainly by enabling access to diversified knowledge and by fostering co-development of customized solutions.

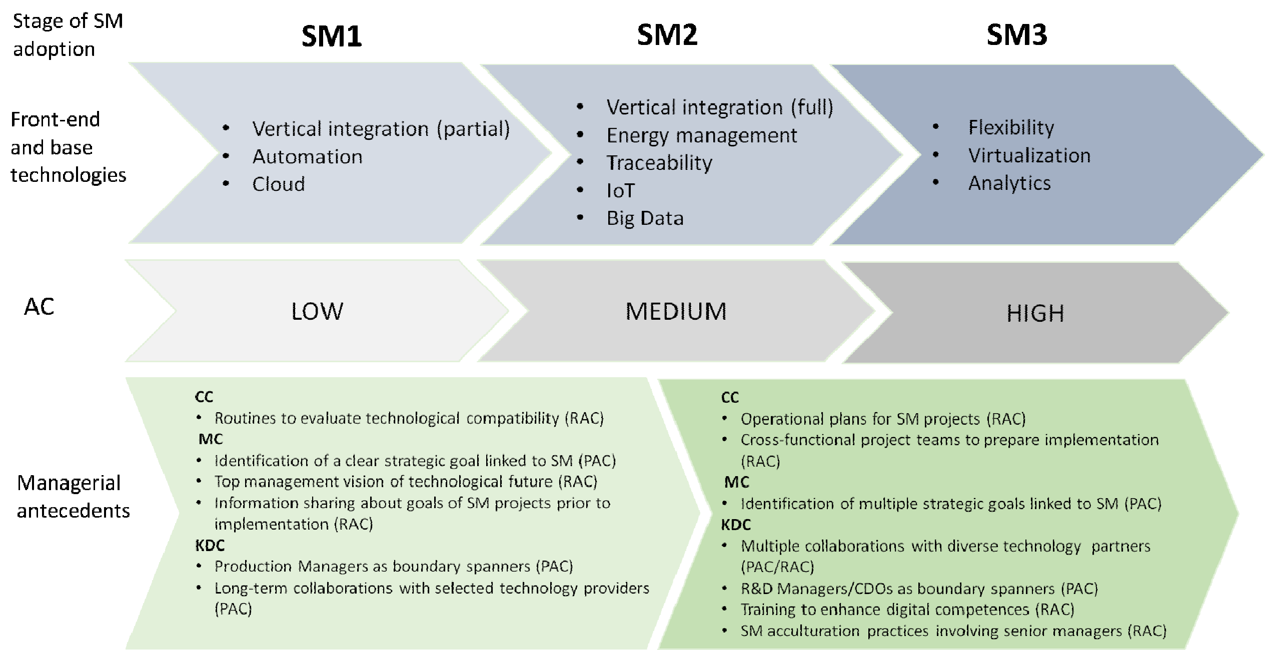

Figure 7: Managerial antecedents supporting SM knowledge absorption

4.6 Discussion

Unlike previous technological paradigms, the digital transformation calls firms to tackle adaptation to a constantly evolving technological target (Sousa-Zomer et al., 2020; Warner and Wäger, 2019), thus entailing the criticality of dynamic capabilities that enable firms to rapidly respond to the challenges and exploit emerging opportunities. In this direction, this study has explored how a key dynamic capability, i.e. the capacity to absorb external knowledge, enables adoption of more advanced SM stages. This section discusses the main findings and contributions of the study in light of previous research.

First, advancement in SM goes hand-in-hand with the development of firms' AC along both dimensions of PAC and RAC. In particular, advancements in SM are clearly enabled by greater capacity to pro-actively search technological opportunities and to leverage internal expertise to decompose new inflows of SM knowledge. Further, more mature stages of SM are associated with a greater capacity to transform and customize SM solutions to the firm's own needs and by the ability to successfully modify employee's work practices. Previous research investigating earlier technological paradigms (Gomez and Vargas, 2009; Lin, 2014) recognized that AC increases the likelihood of adoption of new process technologies. However, technology adoption was generally viewed as a fixed target state enabled by firm's AC. With respect to this conceptualization, this study suggests that the knowledge absorption capacity needs to evolve while firms progress in SM. Since each technological stage achieved forms the basis for the subsequent leap in knowledge absorption capacity (Todorova and Durisin, 2007), organizations need to be in continuous adjustment mode (Sousa-Zomer et al., 2020).

The study has also shed light on how managerial antecedents support PAC/RAC and enable progression in SM. Concerning PAC, results assign an important role to MC and KDC. Concerning MC, given the rich and evolving digital technological landscape (Culot et al., 2020), the identification of clear strategic goals linked to SM adoption is crucial to orient the search for new technologies. The importance of integrating Industry 4.0 projects within a strategic vision for the company had previously been acknowledged (Moeuf et al., 2020; Raj et al., 2020) but had not been empirically linked to the firms' knowledge search practices. Further, case findings show that, as firms progress in SM adoption, they pursue a broader set of strategic goals tied to SM, therefore shedding light on the need to align strategic priorities, knowledge base and technology policies in order to achieve successful SM adoption and suggesting research opportunities in the exploration of manufacturing strategies and digitalization.

With respect to KDC, results highlight the capacity to expand the breadth and variety of the network of technology partners. Case evidence clearly pinpoints that SM3 firms exhibit a far richer network than SM2, which includes universities, start-ups and research centres (de Araújo Burcharth et al., 2015; Laursen and Salter, 2006; Spithoven et al., 2010). As underlined by literature (Benitez et al., 2020), SM is idiosyncratic with respect to previous technological paradigms (e.g. IT) because it is not a monolithic body of knowledge but rather an array of diverse technologies (Frank et al., 2019). Therefore, establishing a broad and diverse network of technology partners facilitates access to complementary SM knowledge. In particular, SM3 firms carry out baseline, more exploitative applications together with traditional technology providers, whereas more explorative and custom-made solutions are developed with research institutions and start-ups. In this respect, results add to extant literature by providing a more nuanced analysis of the role of different types of external knowledge sources in the context of SM innovation. Although our findings can be justified with the heterogeneity of the SM knowledge base, we acknowledge that they contrast with recent findings suggesting a non-significant impact of search breadth for adoption of digital technologies (Lorenz et al., 2020). In our view, the fact that our study looks at the adoption of "bundles" rather than at specific technologies could explain why the value of a diversified network emerges. At any rate, the misalignment in findings calls for further research on technology collaborations.

As technology adoption and usage becomes more exploratory, KDC need to evolve and responsibilities for SM projects shift to CDOs and R&D managers. In this respect, our results contribute to throw light on the required profile for SM leaders (Mittal et al., 2018). Previous SM research has generically acknowledged the importance of digital transformation leaders to optimize the alignment of technological solutions and industrial needs (Mittal et al., 2018; Moeuf et al., 2020). Grounding our results in the AC literature (Volberda, 1996) has allowed providing first-hand evidence on the boundary spanning role that CDOs and R&D managers play in the process of SM knowledge assimilation and, in particular, in contributing to resolve the conflict perceived among the previous well-established IT logic and the SM logic (Tumbas et al., 2018).

All three types of managerial antecedents investigated sustain RAC in the transition towards more advanced SM stages. In particular, with reference to CC and adding to previous research holding that planning is needed to ensure digitalization's success (Horváth and Szabó, 2019), findings show that SM3 firms devise specific operational plans for SM implementation. Such plans provide evidence of the importance of adaptive and integrative capacities, since they handle technological compatibility and other technological aspects in parallel to employees' skill gaps and envision training activities (Brettel et al., 2014; Cagliano et al., 2019).

Findings also point that MC is a relevant antecedent of RAC through information provision to subordinates and socialization capabilities. Specifically, irrespective of SM advancement, findings confirm the criticality of effective management communication capabilities to challenge existing practices and expedite alignment to required behaviours (Jansen et al., 2005; Lenox and King, 2004). New and interesting insights are offered by evidence that SM3 firms adopt acculturation practices to provide senior managerial roles with competences in dealing with non-traditional technology partners (Ancarani et al., 2019; Seyedghorban et al., 2020). In this respect findings add to extant literature by stressing the importance of SM competence diffusion not only among subordinates but also among the wider management team. At the same time, some of the practices adopted (e.g. gaining familiarity with start-ups and innovation incubators) can be seen as socialization tactics (Bouguerra et al., 2021; Jansen et al., 2005) used by SM3 firms to align background knowledge among senior management and therefore build wider consensus for the SM strategy.

CHAPTER 5. Linking competitive priorities, SM advancement and organizational micro-foundations

5.1 Purpose

The previous chapter has suggested research opportunities in the exploration of the link between manufacturing strategies and digitalization. Operations Strategy literature recognizes that a firm's business strategy guides decisions concerning process technology and the organization (Rosenzweig et al., 2010). However, there is still a lack of understanding of whether SM is informed by firms' competitive priorities. Additionally, the role that organizational micro-foundations play in the relation between strategy and SM is not known. To close these gaps, this chapter uses survey data from 234 firms operating in the automotive component industry to test a model linking competitive priorities and SM advancement. Organizational micro-foundations enabling digital dynamic capabilities are assumed to partially mediate this relation.

This chapter is adapted from: *"Linking competitive priorities, SM advancement and organizational micro-foundations"*[8].

5.2 Positioning of the research

SM envisions the combined use of digital technologies such as Cloud Computing, the Internet of Things, Big Data and Analytics with the goal to enable autonomous, self-optimizing production systems (Frank et al., 2019; Moeuf et al., 2018). SM is expected to become the dominant technological paradigm in manufacturing (Kagermann et al., 2013), as it promises to deliver improvements along several dimensions of operational performance (Ancarani et al., 2019; Dalenogare et al., 2018; Lorenz et al., 2020; Tortorella, Giglio, and van Dun, 2019) and can therefore sustain manufacturing industries facing multiple competitive pressures (Kamble, et al., 2020). For instance, Volkswagen Group in collaboration with Amazon Web Services has built a company-wide industrial cloud with the goal to realize significant cost savings and reduce delivery times. Similarly, Bosch has developed a new generation of flexible collaborative robots that perform fully automated end-of-line inspections, to ensure high-quality products and reduce labor costs.

Despite its relevance, many firms struggle to advance in SM (Raj et al., 2020), resulting in slow adoption and in fragmented diffusion across industries and along supply chains (Moeuf et al., 2020). In particular, while many firms have become acquainted with and have adopted basic sensor solutions (Ancarani, et al., 2019), more advanced technologies such as Big Data and Analytics are

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still relatively scarcely applied, leading to loss of potential benefits. In this respect, understanding the determinants of firms' SM adoption and advancement has been recognized as important and timely (Benitez et al., 2020; Horváth and Szabó, 2019; Lorenz et al., 2020). Currently, empirical investigations of SM have been largely characterised by a technology-based approach, highlighting challenges such as inter-operability, technological legacy and digital knowledge (Dalenogare et al., 2018; Frank et al., 2019), while the potential role of non-technological determinants is still to be fully unveiled (Horváth and Szabó, 2019).

According to Operations Strategy literature, firms' decisions concerning technology adoption are guided by business strategy (Hayes and Wheelwright, 1984; Roth and Miller, 1990; Rozeinweig and Easton, 2010; Ward et al., 1990). In particular, a relation is expected to hold between technological decisions and competitive priorities, i.e., the dimensions of competitive advantage that the manufacturer intends to pursue (quality, delivery, flexibility, and cost) to realize its strategy (Boyer and Lewis, 2002; Leong et al., 1990). In fact, only if technological choices reflect strategic priorities, the firm will be able to develop the intended capabilities, thus leading to contend that competitive priorities may influence SM adoption and the stage of advancement. In this direction, past research concerning IT has suggested that not only technologies may differ according to firms' specific priorities (Yen and Sheu, 2004), but also that more advanced technological applications respond to more challenging strategic priorities (Sanders and Premus, 2002). On the other hand, lack of evidence about a strategy-technology relation has also been offered with respect to other technological innovations (e.g., advanced manufacturing and e-commerce applications) (Boyer, 1998; Huang, Gattiker, and Schroeder, 2008, 2010). Extending the investigation of the influence that firms' competitive priorities have on technological choices to the SM context may shed light on why SM advancement differs across firms and industries and provide useful insights for managers undertaking the digital transition. In particular, it may help understand whether a strong strategic focus underscores the adoption of more advanced technologies or whether more advanced SM technologies are associated to specific competitive priorities.

Mixed previous empirical results concerning the association between strategy and technological choices raise additional questions about whether, when lack of a relation is detected (e.g., Boyer, 1998), this is due to the omission of relevant intervening factors from the analysis (Parthasarthy and Sethi, 1993). In this direction, emerging literature has advanced that, unlike previous technological paradigms, digital technologies pose specific challenges linked to the fact that adopters confront continuously evolving target technologies (Warner and Waeger, 2019) and that they need to grasp technologies that often build on distant knowledge bases (Frank et al., 2019). For this reason, SM advancement may require not solely investments in technology but also the alignment of

organization to technology (Arcidiacono et al., 2022; Horváth and Szabó, 2019; Veile et al., 2019). In particular, designing low-level organizational entities with SM adoption in mind may be instrumental in successfully addressing these challenges (Felin et al., 2012; Sousa-Zomer, Neely, and Martinez, 2020). These entities, namely individuals, processes and structures, are commonly referred to as "organizational micro-foundations" (Felin et al., 2012) and may be critical for the development of key dynamic capabilities (Teece et al., 1997) that support technological advancements in fast evolving environments (Warner and Waeger, 2019).
While the importance of adapting organizational micro-foundations to the SM transition makes sense to managers and academics, there is no empirical analysis exploring the role they play in connecting firms' strategy to firms' SM advancement. Operations Strategy recognizes the importance of aligning strategy not only with the technological structure but also with the organizational infrastructure (Anderson et al., 1989; Leong et al., 1990). However, there is limited empirical analysis exploring the form that the generic concept of "alignment" or "fit" among strategy, technology and organization takes (Wiengarten et al., 2013) and none in the SM context. This analysis is important to shed light on the mechanisms through which the organizational infrastructure influences the strategy-SM link and offers practical guidance to manufacturing executives who are engaged in the SM transformation.

With the goal to address these research gaps, this study seeks to answer the following research questions:

RQ3a: What is the relation between competitive priorities and Smart Manufacturing advancement?

RQ3b. What is the role organizational micro-foundations oriented to Smart Manufacturing play in the relation between competitive priorities and Smart Manufacturing advancement?

In order to answer these questions, this study develops a model linking competitive priorities, SM advancement and organizational micro-foundations oriented to SM. Survey data from 234 firms operating in the automotive component industry is used to test the model using Structural Equation Modeling (Hoyle, 1995). This industry is an appropriate context for this study, because of the intense competition in the sector, which calls firms to clearly define the dimensions along which they want to compete and often requires a focus on multiple strategic goals (Hertenstein and Williamson, 2018). Further, automotive is one of the leading manufacturing sectors in the SM transformation and, in this respect, it is especially suited to offer guidance on the importance of the strategic focus and on how the organization should be leveraged to support strategy and advance in SM (Kamble et al., 2020).

This study responds to recent calls in Operations Management research for expanding empirical SM research (Koh et al., 2019; Culot et al., 2020) and contributes to literature in different ways. First, it extends research on determinants of SM advancement (Benitez et al., 2020; Horváth and Szabó, 2019; Lorenz et al., 2020; Moeuf et al., 2020) by shedding light on the influence of competitive priorities and organizational micro-foundations. Second, the study responds to calls for further research on the notion of "alignment" between strategy, organization and technology (Chatha and Butt, 2015) by exploring this relation in the context of SM. Findings also offer guidance to manufacturing executives by suggesting that investments in the organizational infrastructure need to be critically factored in together with investment in SM technologies.

5.3 Construct definition and foundations

5.3.1 Smart Manufacturing

Industry 4.0 envisions the pervasive use of manufacturing technologies related to automation, digitalization and connectivity (Kagermann et al., 2013) and enables an unprecedented integration between physical objects and digital technologies (Dalenogare et al., 2018; Moeuf et al., 2018). Industry 4.0 technologies in firms' production systems are commonly referred to as Smart Manufacturing (SM) (Frank et al., 2019). Given its promise to generate improvements along multiple performance dimensions, SM is consistently identified as a potential source of competitive advantage (Culot et al., 2020; Hofmann and Rüsch, 2017; Wamba et al., 2017).

SM is enabled by a wide array of still-evolving technologies, which have been classified into front-end and base (Frank et al., 2019). The former encompasses technologies that directly support manufacturing activities, such as automation, energy management solutions, virtualization and flexibility technologies. The latter includes Cloud Computing, the Internet of Things (IoT), Big Data and Analytics, which provide front-end technologies with intelligence and connectivity (Tortorella et al., 2020). Since SM technologies are interdependent and complementary in their application, advancement in SM calls manufacturers to interconnect different blocks of SM technologies rather than substituting one with the other (Frank et al et al., 2019). Therefore, firms must think systemically in respect to SM adoption (Dalenogare et al., 2018).

SM advancement brings about increasingly sophisticated digital operational capacities. Moeuf et al. (2018) envision four levels of operational capacities, namely monitoring, control, optimization and autonomy. Monitoring is the simplest capacity, whereby SM is exploited to supervise the status of machines and processes and to issue alerts (Civerchia et al., 2017). Control enables the detection of situations that require decision from operators. Monitoring and control capabilities are pre-requisites for the optimization of production processes and allow predictive diagnostics and maintenance (Chang et al., 2022). The final stage entails autonomous, self-learning and self-optimizing production systems, thus minimizing the need for operators' decisions and interventions (Lee et al., 2018). Baseline operational capacities, such as monitoring and control, can be achieved by interconnecting a limited set of SM technologies, such as the IoT and Cloud, which allow linking physical products and machines to the internet environment and enable data storage and retrieval (Tao et al., 2018). Optimization and autonomy require the interconnection of a broader range of technologies. To exemplify, Chang et al. (2022) conceptualize a production system that optimizes energy consumption by integrating Cloud, IoT, Big Data and Analytics. Similarly, Bauer Bauernhansl, and Sauer (2021) propose an architecture that automatically adjusts production planning and control, which is enabled by a large set of interconnected SM technologies, including, IoT, Analytics and virtualization technologies.

5.3.2 Organizational micro-foundations as enablers of dynamic capabilities

To shed light on firm-level phenomena such as technological advancement, focusing on low-level tangible entities within organizations may be required (Barney and Felin, 2013; Felin and Foss, 2005). Low-level entities, commonly referred to as "organizational micro-foundations" (OMF henceforth), can explain cross-firm variations (Abell et al., 2008; Teece, 2007), as they are considered key constituents of organizational routines and capabilities (Felin et al., 2012; Sousa-Zomer et al., 2020). Felin et al. (2012) identify three categories of distinct, though closely interacting OMF, namely individuals, processes and structures. Individuals shape organizational capabilities through their actions and by bringing human capital (e.g., skills, experience, capacities) to an organization (Felin and Foss, 2005). Processes enable discovery of relevant information and facilitate its circulation and incorporation within firms (Teece, 2007). Structures set the context for interactions within and across organizations and influence coordination and integration between individuals, knowledge development and sharing, and information processing (Wilden et al., 2013).

Key to technological innovation, OMF underpin the development of dynamic capabilities, which assist an organization in building, reconfiguring and integrating internal and external competencies to face changing environments (Teece, 2007; Teece et al., 1997). Dynamic capabilities have been recognized as critical for the successful adoption of past innovations, including robotics and computer-aided design (Gomez and Vargas, 2009), and information systems (Zhang et al., 2018). In the same direction, the dynamic capability framework has been recently proposed as an especially suitable theoretical lens for the study of digitalization and SM adoption (Lorenz et al., 2020; Warner and Waeger, 2019). In fact, in order to successfully navigate the highly dynamic SM technological environment, perspective adopters need to develop ad hoc digital dynamic capabilities (Warner and Waeger, 2019) to: (i) sense trends and opportunities tied to adoption of fast evolving technologies; (ii) seize opportunities and make sound investment decisions; (iii) transform the resource base to execute a digital strategy (Arcidiacono et al., 2022; Sousa-Zomer et al., 2020). Section 3 will elaborate on the role that OMF play in facilitating SM advancement.

5.3.3 Competitive priorities

There is consensus that the competitive priorities (CP henceforth) of cost, quality, delivery and flexibility identify the four key dimensions along which firms compete (Boyer and Lewis, 2002; Leong et al., 1990). CP signal the strategic emphasis on developing a set of manufacturing capabilities with the aim to create competitive advantage (Rozeinweig and Easton, 2010). Over time, the debate concerning CP has revolved around two competing perspectives: the trade-off and the cumulative model. The former holds that production systems can be designed to excel in one manufacturing capability, but always at the expense of the others (Skinner, 1969). In fact, unless slack in the system exists (e.g., obsolete technology, inefficient layout), manufacturers must prioritize competitive dimensions and allocate scarce resources accordingly (Boyer and Lewis, 2002). Conversely, the cumulative model argues that in a world of ever-increasing competition, firms simultaneously focus on multiple CP to remain competitive. In fact, CP might be complementary rather than mutually exclusive, as existing capabilities (e.g., quality) can support the development of other ones (e.g., cost) (Ferdows and De Meyer, 1990; Schoenherr et al., 2012; Schroeder et al., 2011).

In order to build operational capacities building and achieve superior performance, CP must orient strategic decisions concerning manufacturing structures, which include decisions concerning technology adoption (Ward et al., 1990), as well as infrastructural decisions such as those concerning the organization (Hayes and Pisano, 1996; Rosenzweig and Easton, 2010). The match of strategic priorities with technology and organization has often been referred to using the concept of "fit" or "alignment" (Bergeron et al., 2004; Chatha and Butt, 2015; Fiedler, 1964; Nadler and Tushman, 1980). According to the fit perspective, in order for a firm's performance to accrue, congruence must exist among CP, technologies, and the organization, while misalignments give rise to dysfunctions (Kathuria and Partovi, 2000; Ketokivi, 2006; Rosenzweig and Easton, 2010; Wiengarten et al., 2013). Section 3 will elaborate on the need for congruence among CP, OMF (reflecting organizational level decisions) and SM advancement (manifestation of firm’s technology decisions) and on the specific form that “fit” takes in the context of SM.

5.4 Model development

5.4.1 CP and SM advancement

Operations Strategy holds that manufacturers' decisions concerning technology are guided by the firm's or plant's CP (Boyer and Lewis, 2002; Hayes and Wheelwright, 1984; Rosenzweig and Easton, 2010). Consistent with this view, Yen and Sheu (2004) find that flexibility and quality priorities correspond to distinct ERP implementation practices. In the context of IT, Sanders and Premus (2002) offer evidence of a positive association between quality and flexibility priorities and the degree of IT sophistication. However, evidence of the CP-technology relation is mixed. In fact, Boyer (1998) finds that advanced manufacturing technologies are not associated with any of the four CP. Similarly, Huang et al. (2008; 2010) find no relation between the degree to which plants emphasize CP and the adoption of e-commerce applications, which leads the authors to conclude that the strategy–technology relation is more prescriptive than descriptive of how organizations actually behave.

In the context of SM, we embrace the traditional tenet of Operations Strategy and contend that strategy guides firms' decisions concerning SM adoption and advancement. A key reason is linked to the fact that SM implementation entails a cumulative and path-dependent process (Arcidiacono et al., 2022; Frank et al., 2019; Sousa-Zomer et al., 2020), which needs to be planned and integrated within a strategic vision (Moeuf et al., 2020; Raj et al., 2020). Additionally, advancing in SM requires significant financial resources, which may make it profitable only in the medium to long term and therefore requires a strategic perspective (Galati and Bigliardi, 2019).

Turning to the relation between CP and SM, unlike previous technological breakthroughs, SM technologies deliver improvements along multiple performance dimensions (Culot et al., 2020; Dalenogare et al., 2018), thus giving manufacturers incentives to advance in SM irrespective of whether they compete on cost, quality, delivery, or flexibility. To illustrate, the achievement of optimization and autonomy capacities by integrating Cloud, IoT, Big Data and Analytics may serve the purpose of improving cost performance (Agarwal and Brem, 2015) but also product quality (Alexopoulos et al., 2016) and flexibility (Frank et al., 2019).

A second important point is that SM advancements, while delivering growing operational benefits, are however accompanied by increasing costs and implementation complexity, stemming from potential technology compatibility issues (Frank et al., 2019) and from modifications to existing process configurations (Hofmann and Rüsch, 2017). In this light, advancement in SM may be justified when the firm faces more challenging strategic goals (Sanders and Premus, 2002). To illustrate, if competing on cost is not a pressing priority, firms might limit their focus on achieving monitoring capacity. In fact, monitoring allows productivity improvements arising from availability of real time information and can be achieved via the introduction of easy-to-deploy sensor solutions (Agarwal and Brem, 2015). As focus on cost intensifies, firms might consider progressing towards more advanced operational capacities, such as optimization, which enables greater cost reductions through the pursuit of optimal configurations of manufacturing resources via the analysis of real-time machine data (Chen et al., 2015). Similarly, if emphasis on quality is limited, firms might find sufficient to develop monitoring capacity, in order to issue alerts in case deviations from process stability are detected (Kucukoglu et al., 2018). As quality goals become more ambitious (e.g., "Zero Defect"), firms might want to invest in autonomous systems, with the aim of automatically adjusting process parameters to changing conditions (Alexopulos et al., 2016). The above line of reasoning leads to the formulation of the following hypothesis:

H1: More challenging CP are positively associated with SM advancement

5.4.2 Impact of OMF on the relation between CP and SM advancement

The previous section has argued that manufacturers are expected to build more advanced SM capacities according to the strength of the competitive priorities they select. In what follows, we complement the above line of reasoning and build on Operations Strategy literature to argue that strategy also drives the design of OMF. We then draw on Strategic Management and SM research to make the case that OMF enable SM advancement. Putting these two claims together, we then formulate the hypothesis that OMF partially mediate between CP and SM advancement.

CP and OMF: CP are expected to guide not only decisions concerning technology but also those regarding human resources, management capabilities, and organizational processes and structures (Anand and Gray, 2017; Mascarenhas, 1984; Robb and Xie, 2001). In fact, developing an organization congruent with the chosen CP (Hayes and Wheelwright, 1984; Leong, Snyder and Ward, 1990) ensures that strategy is effectively implemented (Chandler, 1962). From a different perspective, strategic management studies recognize that strategy shapes OMF (Barney and Felin, 2013; Felin et al., 2012) that underscore the development of dynamic capabilities (DaSilva and Trkman, 2014; Teece, 2007). Contextualizing these claims within SM adoption and advancement, both research streams suggest that a strong strategic emphasis and more challenging strategic goals are expected to generate stronger incentives to develop OMF oriented to the SM transformation (Warner and Waeger, 2019).

OMF and SM advancement: The dynamic capability lens suggests that OMF (individuals, processes and structures) can be leveraged for the development of digital dynamic capabilities, which in turn enable the adoption of more advanced SM solutions (Sousa-Zomer, Neely, and Martinez, 2020). To confer more advanced SM-enabled operational capacities to their processes, organizations need first to understand potential and working principles of fast evolving technologies, such as Big Data and Analytics, which are key to autonomous production systems (Bauer et al., 2021). Next, they are called to choose among multiple competing technologies the most suited to their business needs (Moeuf et al., 2020), and to select technology partners (Arcidiacono et al., 2022). Finally, in-depth changes to work organization are to be introduced (Veile et al., 2019). In this respect digital dynamic capabilities are expected to support SM advancement by enabling firms to *sense* the potential fast evolving technologies; *seize* SM opportunities by making sound business choices; and *transform* the resource base (Warner and Waeger, 2019).

Individuals contribute to the development of digital dynamic capabilities in various ways. First, firms can support “sensing” by appointing ad hoc roles for the SM transformation, through which they recognise the latest SM technological developments (Moeuf et al., 2020; Mittal et al., 2018). Additionally, top managers play a crucial role in orienting the organization towards SM opportunities by conveying an appealing vision of a firm's technological future (Ghobakhloo, 2020) and by creating a safe space in which experimentation with novel SM solutions is encouraged and failures are tolerated (Veile et al., 2019). Next, “seizing” is ensured by digital-savvy employees who recognize applications suited to business needs (Kiel, Arnold, and Voigt, 2017). Finally, “transforming” is supported by ad hoc middle and executive roles in charge of executing the SM roadmap and of integrating technologies across activity domains (Tumbas et al., 2018). Top management support also enhances a firm's ability to transform the resource base by reducing internal resistance towards the digital transformation (Horváth and Szabó, 2019; Saabye et al., 2022).

As for processes, routines aimed at performing regular market scanning ensure that organizations constantly monitor the technological environment and enable “sensing” of novel SM applications (Lorenz et al., 2020). Next, “seizing” is supported by the definition of operational plans for SM adoption (Arcidiacono et al., 2019), through which firms select technological applications suited to their strategic priorities (Veile et al., 2019). “Transformation” is enabled by information sharing processes and socialization tactics, which foster employees' participation in ideation processes and contribute to creating trust towards the digital transformation (Moeuf et al., 2020).

Finally, concerning structures, “sensing” and “seizing” are fostered by a network of collaborations with SM technology partners that facilitates SM knowledge circulation and supports firms in detecting new technological trends (Benitez et al., 2020). Structures also support “transforming” in two main ways. First, cross-functional project teams that combine technical expertise and human resource management know-how ensure that SM technologies are accepted by employees (Pozzi et al., 2021). Additionally, agile organizational structures allow to fully exploit the potential of SM by enabling decentralized and faster decision making (Veile et al., 2019).

This line of reasoning implies that OMF act as mediators in the relation between CP and SM advancement, as manufacturers are expected to develop OMF that support the competitive priorities they have chosen to achieve more advanced SM-enabled capacities. Based on the above discussion, the following hypotheses are formulated (Figure 8):

H2: *More challenging CP are positively related to OMF oriented to SM*

H3: *OMF oriented to SM are positively related to SM advancement*

H4: *The relation between CP and SM advancement is partially mediated by OMF*

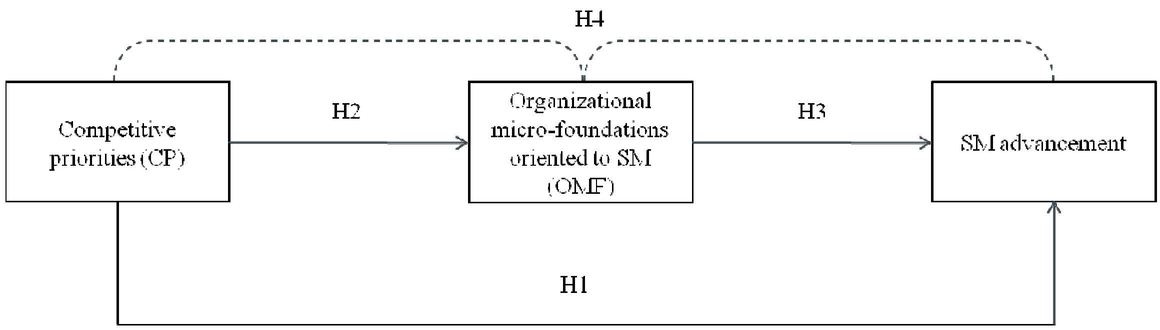

Figure 8: Model and hypotheses

5.5 Methods

5.5.1 Data collection

Survey data was used to test the model developed, following a non-random approach in the selection of participants (Smith, 1983). Specifically, firms that operated in the automotive component industry and had adopted at least some minimum levels of SM were targeted.

A large European OEM in the automotive component industry provided an initial list of about 800 Original Equipment Manufacturers (OEMs) and OEMs' suppliers operating in the same sector. The list of contacts was carefully verified and duplicate or incomplete contacts were deleted. An invitation letter with the link to the questionnaire was sent to the CEOs of 569 companies. The CEOs were asked to complete the questionnaire only if they had adopted at least one SM technology (Frank et al., 2019). Respondent of multi-plant firms were asked to reply with reference to the lead plant for SM, defined as the most advanced plant in terms of SM within the firm (Ferdows, 1997). The final response rate was 41%, corresponding to 234 complete responses. Over half of the respondents (52%) were top managers (e.g., CEOs, CDOs, R&D Managers), while remaining respondents held middle management positions (e.g., Plant Managers, Quality Managers). For the most part (64%), respondents claimed to have a seniority in their current role of more than 5 years. Characteristics of firms included in the sample are reported in Table 12.

Table 12: Firms' characteristics (n=234)

Size			**Country**		
> 249 employees	147	63%	Germany	84	36%
50 - 249 employees	74	32%	China	27	12%
< 50 employees	13	5%	France	17	7%
			Italy	14	6%
Industry sector (NACE code)			India	14	6%
C25: Manufacture of fabricated metal products	65	28%	United States	12	5%
C24: Manufacture of basic metals	52	22%	Spain	12	5%
C22: Manufacture of rubber and plastic components	46	20%	South Korea	8	3%
C28: Manufacture of machinery and equipment n.e.c.	26	11%	Japan	7	3%
Other	45	19%	Other	39	17%

5.5.2 Measurement

CP were measured using the scales for cost, quality, delivery, and flexibility priorities validated by Boyer and Lewis (2002). A five-point Likert scale was used both for CP and OMF, with 1 indicating "no importance" and 5 "absolutely critical". Nine items with statements concerning OMF oriented to SM were newly developed by the research team building on recent SM literature (Table 13). In particular, items capturing the existence of individuals, processes, and structures that are expected to support SM were discussed among the author team and pre-validated with short telephone interviews with a small groups of manufacturing executives. Agreement with the statements was measured using a five-point Likert scale. SM-enabled operational capacities (monitoring, control, optimisation, autonomy) were used as proxy for SM advancement and were measured with a single item on a four-point scale, with 1 indicating the lowest capacity, i.e., "monitoring" and 4 indicating the highest capacity, i.e., "autonomy" (Ancarani et al., 2019; Moeuf et al., 2018). A visual representation of the four capacities in ascending order of complexity and expected performance benefits, together with a short description of each capacity, was also provided in order to facilitate understanding. Respondents were asked to indicate the most advanced capacity achieved.

Table 13: Survey items for organizational micro-foundations oriented to SM

	Survey items	SM literature
Individuals	We have appointed dedicated roles for SM	Moeuf et al., 2020; Mittal et al., 2018 Tumbas, Berente, and Brocke, 2018
	We have invested in digital competences training for employees	Horváth and Szabó, 2019; Kiel, Arnold, and Voigt, 2017
	Our top management strongly supports SM	Ghobakhloo, 2020; Horváth and Szabó, 2019; Saabye, Kristensen, and Wæhrens, 2022; Veile et al., 2019
Processes	We scan the market for new SM solutions of value	Arcidiacono et al., 2022; Lorenz et al., 2020
	We have a clear operational plan for SM implementation	Arcidiacono et al., 2019; Veile et al., 2019
	Our staff is fully informed on the goals of SM projects	Moeuf et al., 2020; Veile et al., 2019
	Our employees exchange best practices concerning use of SM	
Structures	We have multiple collaborations in the field of SM	Benitez et al., 2020; Lorenz et al., 2020; Mittal et al., 2018
	We have cross-functional integration teams for SM projects	Pozzi et al., 2021
	We adopted an agile organizational structure to fully exploit SM	Veile et al., 2019

5.5.3 Common method bias and non-response bias

Several procedural techniques were adopted to minimize common method bias (Podsakoff et al., 2012). During the design phase, dependent and independent variables were separated within the questionnaire and a statement was placed at the beginning of the questionnaire to inform respondents that responses would have been used only for research purposes and aggregated with the responses of others. Additionally, respondents were guaranteed anonymity of responses. Next, the questionnaire was preliminarily administered to four experts (2 academics and 2 practitioners), who suggested minor improvements to reduce ambiguity. Finally, the selection of respondents holding managerial roles and exhibiting expertise in SM ensured the necessary experience concerning the issues of interest. A Harman' single factor test was conducted, including all measures (Malhotra et al., 2006). Results suggest that a single factor accounts for 32.49% of the total variance, below the 50% threshold. A common latent factor test was additionally performed (Podsakoff et al., 2012). The χ^2 difference test performed between the unconstrained and the constrained model revealed that the two models are invariant, thus confirming that common method bias is not a concern in this study.

Non-response bias was also tested. The survey was initially administered in March 2021 and 93 replies were received by April 2021. After two follow-up rounds 141 additional replies were submitted by June 2021. Comparison between early and late responses show no significant differences, thus suggesting that non-response bias does not affect the study (Armstrong and Overton, 1977).

5.5.4 Constructs' validation

Although the CP scales had already been validated (Boyer and Lewis, 2002), criteria for discriminant validity and composite reliability were not met for our sample, thus hinting at the existence of a different underlying construct structure and suggesting running Exploratory Factor Analysis. Factor analysis with varimax rotation indicated two factors (eigenvalues > 1) (Table 14). Scale purification was undertaken using a combination of statistical and judgemental criteria (Wieland et al., 2017). Four items were removed from the scales because they exhibited high cross-loadings (Hair et al., 2014) and were not judged essential to capture the constructs' meaning (Lawshe, 1975). The resulting first construct includes items from the cost, quality and delivery scales (CP_CQD) while the second construct comprises the flexibility items (CP_F).

Exploratory Factor Analysis on items for OMF produced a single factor with eigenvalue larger than one (eigenvalue 5.607; 58.065% of total variance explained) labelled 'OMF' (Table 15). The existence of a single factor in place of the expected three can be justified in light of literature on organizational micro-foundations, which points to a close correlation between individuals, processes and structures (Felin et al., 2012).

Table 14: Exploratory Factor Analysis to validate the competitive priority constructs

	Competitive priorities (CP)						
	Items	**Mean**	**Std dev.**	**Communnalities**	**Factor loadings**		
					1	**2**	
CPC1	Reduce inventory	3.799	0.989	0.478	0.440	0.355	*Excluded*
CPC2	Increase capacity utilization	4.436	0.740	0.684	**0.526**	0.215	
CPC3	Reduce production costs	4.500	0.793	0.662	**0.669**	0.157	
CPC4	Increase labor productivity	4.355	0.768	0.630	**0.596**	0.294	
CPQ1	Provide high performance products	4.456	0.812	0.603	**0.592**	0.179	
CPQ2	Offer consistent, reliable quality	4.684	0.610	0.656	**0.565**	0.250	
CPQ3	Improve conformance to design specifications	4.128	0.918	0.694	**0.744**	0.212	
CPD1	Provide fast deliveries	4.214	0.816	0.548	0.585	0.420	*Excluded*
CPD2	Meet delivery promises	4.449	0.813	0.716	**0.692**	0.379	
CPD3	Reduce production lead time	4.192	0.840	0.684	**0.568**	0.244	
CPF1	Offer a large number of product features	3.556	1.100	0.460	0.337	0.356	*Excluded*
CPF2	Offer a large degree of product variety	3.530	1.154	0.533	0.378	0.423	*Excluded*
CPF3	Make rapid design changes	3.462	1.081	0.623	0.285	**0.586**	
CPF4	Adjust capacity quickly	3.957	0.916	0.692	0.292	**0.756**	
CPF5	Make rapid volume changes	3.714	0.953	0.649	0.189	**0.853**	
CPF6	Adjust production mix	3.722	0.974	0.670	0.242	**0.688**	
	Extraction sums of squared loadings				*6.968*	*1.551*	
	% of variance				*43.270*	*9.205*	
	Kaiser-Meyer-Olkin measure of sampling adequacy				*0.899*		
	Bartlett's test of sphericity (χ^2/df)				*1760.088/120 **		

*p-value < 0.01

Table 15: Exploratory Factor Analysis to validate the OMF construct

	Organizational micro-foundations oriented to SM (OMF)				
	Items	**Mean**	**Std. dev.**	**Communnalities**	**Factor loadings**
OMF1	We have appointed dedicated roles for SM	3.41	0.896	0.652	0.787
OMF2	We have invested in digital competences training for employees	3.80	0.939	0.522	0.512
OMF3	Our top management strongly supports SM	4.15	0.799	0.516	0.671
OMF4	We regularly scan the market for new SM solutions of value	3.50	0.849	0.664	0.792
OMF5	We have a clear operational plan for SM implementation	3.30	0.891	0.661	0.811
OMF6	Our staff is fully informed on the goals of SM projects	3.31	0.850	0.614	0.757
OMF7	Our employees exchange best practices concerning use of SM	3.33	0.820	0.650	0.775
OMF8	We have multiple collaborations in the field of SM	3.49	0.891	0.499	0.663
OMF9	We have cross-functional integration teams for SM projects	3.49	0.895	0.661	0.793
OMF10	We adopted an agile organizational structure to fully exploit SM	3.27	0.834	0.548	0.712
	Extraction sums of squared loadings				*5.607*
	% of variance				*58.065*
	Cronbach's alpha				*0.917*
	Kaiser-Meyer-Olkin measure of sampling adequacy				*0.923*
	Bartlett's test of sphericity (χ^2/df)				*1359.243/45**

*p-value < 0.01

Next, Confirmatory Factor Analysis was conducted to verify convergent validity and uni-dimensionality. Goodness-of-fit was judged by means of multiple fit indices (Table 16) suggesting satisfactory fit (Kline, 2005). For all constructs, items exhibited loadings greater than 0.5 (Fabrigar et al., 1999). Discriminant validity was tested via the average variance extracted (AVE), showing that square root of AVE was always higher than the correlation between constructs (Fornell and Lacker, 1981). Convergent validity was tested using the composite reliability index (CR), which was always above 0.7 (Hair et al., 2014).

Table 16: Confirmatory Factor Analysis

First order factor ***(scale)***		**Items**	**Loading (SE)**
Competitive priorities (CP)			
p-value=0.0561; $\chi^2/df=2.07$; RMSEA=0.069; CFI=0.955; TLI=0.942; SRMR=0.047			
AVE=0.476; CR=0.87			
Cost, quality, delivery (CP_CQD) *(Boyer and Lewis, 2002)*	CPC2	Increase capacity utilization	0.584 (0.047)
	CPC3	Reduce production costs	0.696 (0.038)
	CPC4	Increase labor productivity	0.725 (0.037)
	CPQ1	Provide high performance products	0.654 (0.041)
	CPQ2	Offer consistent, reliable quality	0.626 (0.043)
	CPQ3	Improve conformance to design specifications	0.797 (0.030)
	CPD2	Meet delivery promises	0.761 (0.031)
	CPD3	Reduce production lead time	0.619 (0.044)
AVE=0.593; CR=0.852			
Flexibility (CP_F) *(Boyer and Lewis, 2002)*	CPF3	Make rapid design changes	0.518 (0.053)
	CPF4	Adjust capacity quickly	0.667 (0.041)
	CPF5	Make rapid volume changes	0.824 (0.028)
	CPF6	Adjust production mix	0.842 (0.026)
Organizational micro-foundations oriented to SM (OMF)			
p-value=0.0655; $\chi^2/df=1.64$; RMSEA=0.052; CFI=0.986; TLI=0.979; SRMR=0.030			
AVE=0.484; CR=0.919			
	OMF1	We have appointed dedicated roles for SM	0.800 (0.028)
	OMF2	We have invested in digital competences training for employees	0.599 (0.053)
	OMF3	Our top management strongly supports SM	0.646 (0.042)
	OMF4	We regularly scan the market for new SM solutions of value	0.796 (0.029)
	OMF5	We have a clear operational plan for SM implementation	0.799 (0.027)
	OMF6	Our staff is fully informed on the goals of SM projects	0.716 (0.036)
	OMF7	Our employees exchange best practices concerning use of SM	0.742 (0.033)
	OMF8	We have multiple collaborations in the field of SM	0.667 (0.040)
	OMF9	We have cross-functional integration teams for SM projects	0.814 (0.026)
	OMF10	We adopted an agile organizational structure to fully exploit SM	0.685 (0.039)

Finally, pairwise correlations among constructs were checked (Table 17).

Table 17: Multiple correlation matrix (Cronbach alphas on the main diagonal)

		Mean	St. dev.	1	2	3	4
1	CP_CQD	4.383	0.399	**0.867**			
2	CP_F	3.715	0.704	0.625**	**0.843**		
3	OMF	3.520	0.562	0.279**	0.226**	**0.917**	
4	SM advancement	2.691	0.929	0.088	0.137*	0.328**	-

5.5.5 Hypotheses testing

Covariance-based Structural Equation Modelling was used to test the hypotheses, using full maximum likelihood as estimator (Kline, 2005). Figure 2 reports standardized path coefficients and standard errors in brackets.

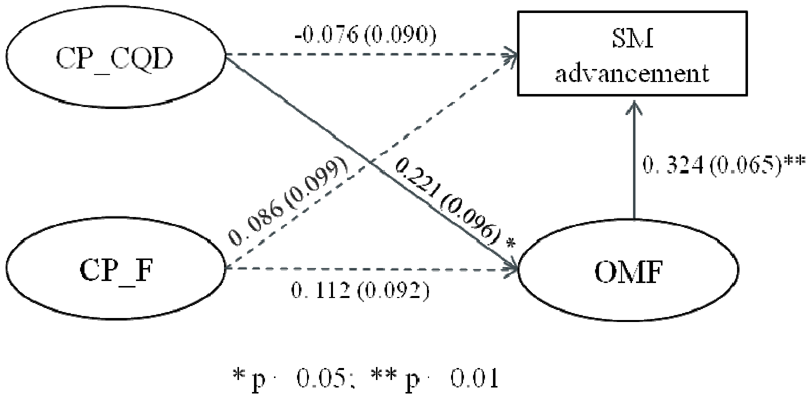

Figure 9: Path coefficients (standard errors in brackets)

Goodness-of-fit indices indicate that the empirical data suit well the theoretical model (χ^2/df=1.622; CFI=0.949; TLI=0.941; RMSEA=0.052; SRMR=0.051). With respect to the direct link between CP and SM advancement, both CP_CQD (-0.076; p>0.05) and CP_F (0.086; p>0.05) exhibit non statistically significant effects. In light of these results, a direct impact of CP on SM advancement cannot be confirmed and therefore H1 is not supported. As for the relation between CP and OMF, results show a positive and significant association between CP_CQD and OMF (0.221; 0.01<p<0.05), while the coefficient for CP_F is not significant (0.112; p>0.05). Therefore, H2 is confirmed for the cost, quality and delivery priority, but not for flexibility. Finally, OMF has a positive and statistically significant relation with SM advancement (0.324; p<0.01), thus confirming H3. To test H4, a mediation analysis was conducted to measure the indirect effect that CP have on SM advancement via OMF. Bootstrapped 95% confidence intervals with 500 re-samplings were computed (Kline, 2005). Results reveal a non-significant indirect impact of CP_F (0.028; p>0.05;

bootstrapped confidence intervals: -0.017 / 0.296), while the indirect effect of CP_CQD is positive and statistically significant (0.072; $p<0.05$; bootstrapped confidence intervals: 0.004 / 0.128). Therefore, H4 is partially confirmed.

5.6 Discussion

This study has endeavoured to investigate the links between CP and SM advancement and to explore the existence of a mediating role of OMF. This section discusses findings in light of previous results and highlights contributions to research and implications for practice.

Previous research has prescribed that technology decisions are guided by strategy, but has provided mixed evidence of the descriptive power of this relation. In fact, while some studies find evidence that firms' specific CP influence the types of technology adopted (Yen and Sheu, 2004) or the level of technological advancement (Sanders and Premus, 2002), others (e.g., Boyer, 1998; Huang et al., 2010) cannot confirm the relation. Our study cannot validate the direct relation between the strength of any of the CP and SM advancement. According to Huang et al., (2010), lacks of a significant relation may be explained by the fact that technology decisions may depend on institutional factors, while being independent of strategic orientation (Parthasarthy and Sethy, 1993). Our results suggest an alternative explanation for the absence of a direct relationship, which is rooted in the concept of strategy-organization-technology alignment (Weingarten et al., 2013; Dohale et al., 2022). While alignment broadly implies that strategy concurrently drives decisions concerning technology and the organization, we suggest that technology advancement in SM critically hinges on decisions concerning the organization. In fact, a key result of the study is that the relation between CP and SM advancement is fully mediated by OMF. Therefore, in the context of SM, more challenging competitive priorities lead manufacturers to shape organization micro-foundations suited for SM. This, in turn, enables digital dynamic capabilities that allow firms to reach more advanced SM operational capacities (Moeuf et al., 2020). This finding complements results of recent qualitative studies, which have suggested a pivotal role of dynamic capabilities for SM (Arcidiacono et al., 2022) and more in general for the digital transformation (Warner and Waeger, 2019). Findings also extend previous quantitative studies that have investigated micro-foundations of digital dynamic capabilities (Sousa-Zomer et al., 2020) by connecting OMF to both strategy and technology advancement.

The pivotal role of OMF can be explained in light of peculiar features of SM relating to knowledge search, capture and exploitation. In fact, unlike previous technological paradigms, SM is not a monolithic body of knowledge (Frank et al., 2019) and its adoption requires the assimilation of evolving technological knowledge (Culot et al., 2020). To facilitate sensing and seizing of SM technological opportunities and transformation of the resource base, firms need to have appropriate people (e.g., digital-savvy employees, SM-supportive leaders) (Saabye et al., 2022), structures (e.g., cross-functional teams, organizational agility) (Pozzi et al., 2021), and processes (e.g., market scanning, structured training, technological information sharing) (Arcidiacono et al., 2022). Further, because these technologies are usually generated by heterogeneous parties, including traditional technology providers, universities and start-ups (Lorenz et al., 2020), firms must value multiple external collaborations to gain access to diversified SM knowledge (Benitez et al., 2020).

A second key result of the study is that SM advancement is linked to a bundled cost, quality, and delivery competitive priority. Therefore, automotive suppliers that adopt more advanced SM also assign greater emphasis to the simultaneous pursue of production efficiency, product performance and delivery. This result is relevant on two grounds. First, it provides evidence that the growing competitive pressures within the automotive supply chain towards reducing production costs, while maintaining quality and delivery targets (Laosirihongthong and Dangayach, 2005; Hertenstein and Williamson, 2018) are manifested in a joint strategic emphasis on these three priorities. The existence of a constructs that bundles these three priorities also indicates that case firms do not view them as trade-offs (Skinner, 1969) and lends support to the idea that manufacturers actually look at SM as a means to develop multiple manufacturing capabilities (Ferdows and De Meyer, 1990; Schoenherr et al., 2012; Schroeder et al., 2011).

Conversely, it comes as a surprise that no significant evidence emerges about the link between the flexibility priority and SM advancement. In fact, one of the awaited and novel advantages of SM is to enable a high degree of flexibility through self-organizing manufacturing systems (Qin and Lu, 2021). Critically, in our study firms emphasizing flexibility do not invest in organizational improvements. Though unexpected, this result recalls similar findings relating to AMT adoption (Boyer, 1998), which showed that manufacturers did not see a connection between investments and increased flexibility. The lower emphasis that firms in the sample place on flexibility may explain the absence of relation: flexibility is the least pressing priority and therefore does not motivate ensuing strategic actions, neither concerning the organization level, nor technology.

CHAPTER 6. Concluding remarks

6.1 Synopsis

Despite its recognized strategic importance, many firms struggle to progress in SM (Raj et al., 2020). Since fragmented adoption has the potential to jeopardize benefits tied to the use of SM technologies, Operations Management research has recognized the value of investigating determinants of SM advancement (Horváth and Szabó, 2019; Lorenz et al., 2020). Previous studies in this field have usually embraced a technology-based approach, which fails to unveil the influence exerted by non-technological determinants (Horváth and Szabó, 2019). The empirical studies presented in this doctoral dissertation aim at expanding extant knowledge by investigating the role played by organizational factors in the SM adoption process.

In particular, **Chapter 2** builds on case evidence from two automotive firms, which represent two polar cases in respect to their stage of SM adoption, to investigate which technological, organizational and environmental factors are relevant in determining the success of SM initiatives. Results of the study suggest that the adoption process is mainly supported by organizational factors in the form of a proactive approach to innovation and early involvement of workers in the process of technological change. Findings also point to the importance of searching and integrating externally generated SM knowledge.

Building on these results, **Chapter 3** introduces absorptive capacity as a suitable and original theoretical lens to investigate firms' progression in SM. In fact, although the peculiar features of SM suggest that the ability to search and incorporate SM-related knowledge might be a crucial dynamic capability that prospective SM adopters should possess, little research had investigated the relation between absorptive capacity and SM adoption and there was no understanding concerning relevant organizational and technological factors driving the development of absorptive capacity in the context of SM. Case study evidence arising from four automotive suppliers confirms that higher levels of absorptive capacity result in higher stages of SM adoption and highlights that the development of absorptive capacity is mainly driven by organizational factors. These results also suggest research opportunities in the exploration of the mechanisms through which absorptive capacity enables progression in SM and of how organizational factors support the development of absorptive capacity.

In this direction, **Chapter 4** explores how absorptive capacity allows firms to progress towards increasingly advanced stages of SM adoption and sets out to investigate how managerial factors - a subset of organizational factors underscoring the capacity of managers to create, extend, or modify the knowledge base of an organization - support absorption of SM knowledge at different stages of SM. Twelve firms, operating as part of the automotive supply chain and exhibiting different stages of SM adoption, constitute the sample. Results suggest that higher levels of absorptive capacity allow firms to detect the potential of highly complex SM technologies and facilitate the introduction of significant changes in employees' work routines. In turn, firms' ability to acquire and assimilate SM knowledge is supported by managerial antecedents encompassing integrative capacities to bridge old and SM technologies, managerial cognition through the clear alignment of SM technologies with strategic goals, and knowledge development capabilities through practices oriented to provide senior managers with SM competences. Case findings also show that progression in SM is accompanied by the pursuit of a broader set of strategic goals and thus suggest exploring in greater depth the link between manufacturing strategies and SM.

In this respect, the existence of a simultaneous alignment between firms' strategy, process technology and the organization constitutes a tenet of Operations Strategy literature. However, in spite of its relevance for both theory and practice, no empirical investigation had been undertaken to shed light on how SM is informed by firms' competitive priorities and on the role that organizational factors play in the relation between strategy and SM. To close these gaps, **Chapter 5** uses data from 234 firms operating in the automotive component industry to test a model linking competitive priorities and SM advancement. Organizational micro-foundations enabling digital dynamic capabilities are assumed to partially mediate this relation. Results suggest that SM advancement is driven by the concurrent focus on cost, quality and delivery, thus indicating that manufacturers use SM to simultaneously develop multiple manufacturing capabilities. Organizational micro-foundations are the transmission mechanism linking competitive priorities to SM advancement.

6.2 Contributions

This doctoral dissertation responds to calls for expanding empirical research on SM (Koh et al., 2019) and offers different contributions to Operations Management literature on the adoption of SM technologies and to practice.

6.2.1 Contributions to theory

This doctoral dissertation contributes to theory by enriching the body of knowledge on non-technological determinants of SM (Arcidiacono et al., 2022; Horváth and Szabó, 2019; Mittal et al., 2018; Moeuf et al., 2020; Veile et al., 2019, among others) and on the relevance of dynamic capabilities for SM (Ancarani et al., 2019; Chen et al., 2015; Sousa-Zomer et al., 2020; Wamba et al., 2017).

In particular, **Chapter 3** and **Chapter 4** provide an analysis of how absorptive capacity evolves to enable more advanced SM stages. Additionally, findings emphasize that SM knowledge absorption builds on a set of managerial factors, whose role has only marginally been accounted for in previous SM research. To illustrate, adjusting supporting roles for the SM transformation emerges as key to market scanning and boundary scanning activities and to managing the network of technology collaborations (Zheng et al., 2019). Next, while managing a network of diverse technology partners is a key tenet from absorptive capacity research (Spithoven et al., 2010; Xia and Roper, 2008), it is only slowly emerging in SM literature (Benitez et al., 2020; Moeuf et al., 2020).

Chapter 5 provides quantitative evidence that SM progression is guided by multiple competitive priorities and highlights that organizational micro-foundations enabling digital dynamic capabilities fully mediate the relation between strategy and SM advancement. This chapter also respond to calls to develop the Operations Strategy literature (Anand and Gray, 2017; Chatha and Butt, 2015). In fact, this stream of literature postulates that competitive priorities influence decisions concerning technology and organizational infrastructure, the empirical relations between these three constructs have remained blurred and subsumed under the generic concept of "alignment" or "fit" among strategy, technologies and organization (Wiengarten et al., 2013). In this direction, this study contributes to shed some light on the nature of alignment in the context of SM, by exploring the concept of fit as mediation (Bergeron, Raymond, and Rivard 2004; Peng, Schroeder, and Shah 2011).

6.2.2 Contributions to practice

The dissertation offers also multiple contributions to practice. In particular, findings from **Chapter 2** show that firms should resist the temptation to solely rely on internal know-how to envision SM initiatives for fear of opportunistic behavior from third-party technology suppliers. In fact, this form of vertical integration is risky given the extremely rapid advancement of SM, which requires access to specific and evolving expertise.

Evidence presented in **Chapter 3** complements this recommendation by showing that SM, more than previous technological paradigms, requires companies to open up to collaborations. Case evidence presented in this study also highlights the progressive nature of firms' SM transformation, in line with the tenets of absorptive capacity literature (Todorova and Durisin, 2007). Given the path-dependency of this process, it is therefore important to not delay the start of the SM transformation, as leap-frogging may be daunting, due to time and effort required to build a network of technology sources and to assess and fill skill gaps. This recommendation is especially valuable for firms operating in sectors such as the automotive, in which smaller suppliers are under pressure to start their SM journey. On the other hand, the progressive nature of the SM transformation entails that resources that SM firms need to commit to SM may be built over time following a digital transformation roadmap.

Findings presented in **Chapter 4** provide guidance to business leaders interested in the SM transformation by showing how managerial factors need to be deployed or enhanced to support SM progression. In particular, results point to the relevance of knowledge development and sharing capabilities to acquire knowledge on a broad range of SM solutions. In this direction, firms are called to progressively expand a network of collaborations with diverse technology sources, and to appoint boundary spanners, whose profiles co-evolve with companies' technology endowment. Findings also highlight the importance of combinative capabilities, which call for creating routines aimed at facilitating integration of new SM equipment with existing configurations of equipment, and of managerial cognition, as exemplified by practices oriented at involving employees in the process of change at early stages.

Along the same lines, the mediating role of organizational micro-foundations in the relation between competitive priorities and SM advancement presented in **Chapter 5**, suggests that firms' SM roadmap must factor in investment in the organizational infrastructure in addition to investment in technology. This result has also implications for the way focal firms in the supply chain support suppliers' process innovation strategies. In fact, several Original Equipment Manufacturers and car makers financially support SM technology acquisition of their suppliers. However, findings of this study suggest that these initiatives may turn out to be of little benefit if not contextually matched by pressures on or collaboration with suppliers to upgrade the organizational infrastructure.

6.3 Limitations and future research directions

Limitations of the research included this dissertation must be acknowledged. First, all studies have been carried out in the automotive industry. As a result, case firms share similar strategic goals and face high pressure to embrace SM. Therefore, the extension of the research to a wider set of industries is valuable for the generalizability of the results. Similarly, generalizability calls for verifying case-study findings presented in **Chapter 2** and propositions developed in **Chapter 3** on a larger scale. Next, analyses in Chapter 3 and **Chapter 4** have focused on intra-organizational factors, while supply chain characteristics and the external environment can also play an important role in determining firms' SM progression. Additionally, since research presented in Chapter 4 does not include firms that have not implemented any form of SM, future research should investigate whether low degrees of potential/realized absorptive capacity constitute a necessary condition to adopt low complexity solutions typical of early stages of adoption. As for **Chapter 5**, the study is not longitudinal since competitive priorities, organizational micro-foundations and SM advancement were measured contemporaneously. Next, the analysis has not included sustainability and innovation, which can be acknowledged as additional strategic drivers of firms' SM adoption. Further, this study considers generic SM-enabled operational capacities. Analysing specific SM practices could be an important extension of this research. Finally, future studies should provide a more granular view of the impact that single organizational micro-foundations have on SM advancement.

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APPENDIX

Interview protocol (ref. Chapter 4)

Instructions: Thank you for taking the time to talk with us today. The goal of this conversation is to discuss the approach, the current status and future projects of your company in respect to Smart Manufacturing (SM). There are no right or wrong answers, or desiderable or undesiderable answers. We would like you to feel comfortable saying what you really think. If you agree, our conversation will be tape recorded. All information gained through this interview will be treated as anonymous.

I. Introduction

1. Your firm was selected to participate in this study as you are a prominent supplier for the automotive sector. Could you please help us understand what is your business strategy?
2. From your point of view, what are the challenges that the automotive sector has faced over the last years? How have these challenges impacted on your firm?
3. How long ago did you start investing in SM? Has there been continuity in your SM efforts?
4. Which are the most significant SM projects you have undertaken? Could you please describe their aim and scope?

II. Absorptive capacity

5. What prompted you to invest in SM? Have you faced any pressure to adopt SM or have you spontaneously recognized its potential?
6. Do you actively search for latest trends/developments in SM or do you rely on mature SM technologies? Why?
7. Could you please describe the process through which you search for new SM solutions on the market?
8. Do you choose ready-made solutions or do you pursue co-developments of customized advanced SM applications? Could you please make some examples?
9. Within your organization, how diffused is knowledge concerning SM technologies you have adopted? Could you please elaborate on this point?
10. Concerning the SM technologies not currently in use at your sites, which ones are you considering in the near future?
11. How have your employees' working routines changed as a result of the introduction of SM?
12. Could you please tell us about any unsuccessful SM project?
13. How has SM contributed to the identification of new opportunities and to addressing key challenges?

III. Managerial antecedents

14. Does the firm's leadership support SM?
15. Within your organization, who is in charge for SM? Can you please describe their responsibilities and tasks?
16. Are different functions (e.g. production, quality, logistics, human resources, etc.) involved in the definition/implementation phase of SM projects? How?
17. How have you chosen your suppliers of technology and what kind of relationship do you have with them?
18. How did you prevent/deal with difficulties concerning the integration of new SM technologies within existing configurations of equipment?
19. How do you make sure that goals and information concerning SM projects are shared with employees?
20. How were workers and management supported in the process of change brought by SM?
21. In the frame of your SM projects, were there new specific employees' skills that you did not possess? Did you hire people with new professional skills or did you train your employees?
22. *(If the firm had to train workers)* Did you face any difficulty in having to train employees who were already within the company?

Table 18: Exemplary coding table - SinterCo (ref. Chapter 4)

Absorptive capacity

Data	1-st order indicators	2-nd order concepts	Theoretical themes
"We have been working for many, many years - since the end of 1990s – with digital systems and entering data into those digital systems. As a result, we have been dealing with digital systems for quite some time now... "	Use of digital technologies has a long tradition in the company	Recognition of potential tied to SM	PAC - Ability to detect opportunities in the environment (Camisón and Forés, 2010; Noblet et al., 2011)
"Frankly we haven't faced any pressure to adopt SM from your key customers... We are getting pressure to have EDI connections, which is what we have already... But in terms of SM I would say that we are a little bit more active maybe than our customers..."	SM adoption does not stem from customers' pressures		
"The story with Additive Manufacuring started about 5-6 years ago… Then it was something quite new in our sector... Initially Additive was used in our tool shop manufacturing. It was really about the design, as additive gave us the capabilities to work on advanced design for our tools… That is how we started with additive, and then we tried to explore how we could include use it for serial production."	Pioneering use of Additive Manufacturing		
"During our SM journey we realized that we can actually use production data also to significantly improve the value for our customers, not just in terms of better quality or whatever, but also in terms of shorter development times, additional services…"	Spontaneous recognition of potential of data sharing		
"I [CDO] and my team regularly turn to our technology partners to see what's new on the market."	Regular market scanning	Frequency and breadth of market scanning	
"Originally, our search was directed at applications aimed at improving productivity, but during the journey we realized that we could achieve much more. We keep our eyes open to detect new possibilities that may arise."	Market scanning with a broad focus		
"We have also been pushing our customers to start common projects, especially in the field of customer-supplier data sharing…"	Common SM projects with customers are encouraged	Reaching customers to push for common projects	
"We have been reaching out to quite a few customers to explain what we are doing in SM."	Sharing of ongoing SM projects with customers		
"We asked ourselves: "How can we make Additive Manufacturing part of our product life-cycle?". So we started investigating different powder materials, different technologies... "	Experimentation concerning choice of materials and technologies	Pioneering experimentation with novel SM applications	
"We started to approach our customers, starting with obvious business cases like rapid prototype manufacturing, sample manufacturing…"	Identification of use cases for novel SM applications		
"Well, I can say that our past experience in the field of digitization has simplied our SM journey… We had already the right mindset and we also possessed part of the digital capabilities we needed."	Internal expertise in the field of digitization paves the way for SM	Use of internal expertise to support assimilation	PAC - Ability to use employees' knowledge, experience and competency in the assimilation and interpretation of new knowledge (Camisón and Forés, 2010)
"Artificial intelligence is definitely in our plan, in our vision… I [CDO] and our Production Manager are starting to assess how we can use automated artificial intelligence and machine learning to automatically improve our processes"	Preparation for next generation technologies		
"Our Quality Manager has been working with a South African startup but also with universities to find promising applications in the field of quality data analytics."	Quality Manager cooperates with different technology partners	Employees' ability to work with technology partners	
"[When working with such diverse technology partners] getting to communicate is often the most difficult thing. We devoted a lot of time and efforts to understand how they work, so to be aligned with our partners."	Organizational efforts to acquire understanding on how to work with diverse technology partners		

Data	1-st order indicators	2-nd order concepts	Theoretical themes
"In our vision the shop floor of the future is fully connected and highly automated. Active communication is implemented between machines, assets, products and people and all the data is captured. In this respect, the ERP and the MES are two crucial assets as they enable vertical and horizontal communication with our machines and that's why have invested to connect over 1800 machines worldwide"	MES and ERP as pillars for active communication with machines on the shopfloor	Understanding of potential and working principles of SM technologies, including those not yet in use at the firm's sites	PAC - Capacity to assimilate new technologies and innovations that are useful or have proven potential (Camisón and Forés, 2010)
"We provide data, we have millions of data in our systems: process data, product data, measurement data… But in order to analyze them or to build a digital model or to use the right analytics tools, you need to have a process understanding, a data understanding… Because there are a lot of assumptions and you need to build up your models, so if you get a better understanding, also the results are much better. Otherwise, you need many loops and very often the data are absolutely not reliable at the end."	Reliability of Analytics depends also on understanding of production processes		
"Additive Manufacturing is quite heavily dependent on the design of parts. In other words, not all parts can be designed for Additive. The second relevant point is volume, as Additive is suited for low volume parts."	Viability of Additive Manufacturing hinges on parts' design and production volume		
"The latest applications on the technological frontier envision the use of artificial intelligence in the form of machine learning to optimize process operating parameters and avoid production of NoK parts. This is not yet in any of our applications, we are not yet at that stage..."	Machine learning can be used for predictive quality, although not currently applied at the firm's site		
"When working with startups the problem is that they do not understand industrial processes and industrial data. But this is a crucial requirement in order to analyze them or to build a digital model..."	SM solutions require partners to combine understanding of technologies and process	Partners' comprehension of processes and technologies	
"It was very helpful to discuss in person with our partners in SM projects, especially when they were able to visit one of our plants to get an understanding about the processes. Of course you can prepare a PowerPoint, but it is not the same... Therefore is good that somebody really sees how our parts are produced and gets an understanding of how data can be used"	Interactions with technology partners to build process understanding		
"One limitation of automated nonconformities identification system is the time needed to program and deploy them, which can take up to 3 weeks. Together with a local startup we have developed a system which leverages on artificial intelligence to reduce deployment time to just one hour."	Co-development of an automated nonconformities identification system with reduced deployment time	Frequency and variety of customizations and co-developments of SM technologies	RAC - Firm's capability to adapt technologies designed by others to its particular needs (Camisón and Forés, 2010)
"We worked with a startup to develop our iDash system, which enables us to monitor all our machines on the shopfloor in every location and to condens data in just a few KPIs, customized based on the user."	Co-development of a system that builds on Big Data and Analytics to monitor operations		
"We partnered up with a car-maker and a technology supplier to co-develop a proprietary Additive Manufacturing technologies which ideally fits our processes."	Co-development of an Additive Manufacturing technology expecially suited to the firm's processes		
"Yes, we have faced some integration issues between old and new equipment, but we have been able to solve them. Overall I cannot say that those are the roadblocks. That was not our case…"	Compatibility between old and new equipment is not a roadblock	Integration between legacy and new SM equipment	
"When we introduced the new MES we made sure to interface it with the digital system we used to perform quality monitoring, so that data could be exchnaged between the two. That was one of our very first SM projects..."	Successful interface of new MES with legacy systems		

Data	1-st order indicators	2-nd order concepts	Theoretical themes
"Additive Manufacturing is suited for low volume parts, while we we were quite a high volume business. Integrating Additive Manufacturing meant extending our product life cycle, so that basically we start earlier and we attract more business as we reach lower volumes. This changed quite significantly our business model..."	Low-volume parts included in the product portfolio as a result of SM	Impact of SM on the business model	RAC - Ability to challenge established thinking or practices (Noblet et al., 2011)
"To exploit Additive we needed a different business approach, as explained before. So in parallel to offering these technologies, we also started offering different services for customers, different interactions, easier, more straight forward, immediate feedback and so on [...] We worked with a few startups to find new ways to interact with customers, to handle orders, because the traditional business is really with standardized procedures and the ERP systems and whatever...while the Additive business is really about flexibility and speed... We introduced an app to interact with our customers in the Additive business. Basically they can ask for a quotation via the app and we can exchange information via the app, so that the entire process is much more flexible and fast"	New ways to handle interactions with customers to make the most of Additive Manufacturing		
"[To sustain the digital transformation] there were a lot of job changes and we had also to hire new people. We built up an IoT team, we appointed data scientists, some IT guys who took care of connecting machines…"	Job changes introduced to sustain the digital transformation	Impact of SM on employees' working routines	
"To generate value out of the real-time production data that we analyze, we needed our shopfloor workers to shift from performing production tasks to becoming agile problem solvers"	Transition of shopfloor workers from performing production tasks to being agile problem solvers		
"One challenge we are facing is about the implementation, when people need to change behavior… And that obviously increases when you do this not just for one plant, for one pilot, but you really work one a global scale… That's something that requires attention and efforts"	Focus on employees' acceptance of change is key to successful implementation	Acceptance of changes brought by SM	
"The shift [in shop-floor workers' routines] was substantial but overall we have managed quite well I can say..."	Changes in employees'working routines have been successful		
"There are always some problems with the plan, because plan tend not to work out 100%... But as of today we have been able to complete all projects we started	All SM projects have been successfully completed	Completion of SM projects	RAC - Application of knowledge and experience acquired in the technological and business fields (Camisón and Forés, 2010)
Our motto has always been: "Let's stop working on the perfect solution, even if it is not perfect, let's go out and let's really focus on implementation". It is better a 75% solution fully implemented than a 100% solution not implemented, so overall I can say that we have been successful with our SM projects"	Focus on implementation phase determines the success of SM projects		
"The fact that we frequently undertake developments of our own proprietary solutions means that is not unusual for us to file patents…"	Patents filed as a result of developments of SM proprietary solutions	Capacity to put SM knowledge into patents	
"The Additive Manufacturing technology we developed is now patented"	Patent has been granted for a proprietary Additive Manufacturing technology		
"There is great market uncertainty in the automotive at the moment. It is quite a tense situation, I would say. Everybody knows that something needs to happen but it is not clear in what direction we will go. [...] What it will really get important for traditional car makers is the time to market, so how quickly they can develop these new solutions, how quickly they can bring them to market... That is what we would say is the biggest challenge overall and SM for us is strategic in this respect".	SM recognized as strategic to face market uncertainty in automotive	Use of SM knowledge to respond to external challenges and gain competitive advantage	
"Our customers often tend to prefer us as suppliers given our focus on the topic of digitalization"	Preferred supplier status stemming from success in digitalization		

Managerial antecedents

Data	1-st order indicators	2-nd order concepts	Theoretical themes
"We have crafted a roadmap for SM implementation, which is quite simple. At first we identified the key project we would like to deliver and also the technology enablers we need: Big Data, AI, augmented reality…"	SM implementation builds on identification of main projects and linked technology enablers	Operational plans for implementation of SM projects	Combinative capabilities (CC)
"Once the concept phase come to an end, we start small pilot projects. If they are successful and we see benefits, we then move to the roll out phase on a global scale. Our motto is 'start small, scale fast'."	SM pilot projects pave the way for global roll-outs		
"This is our SM roadmap… Together with each business function, we have defined one or two SM projects we want to undertake. We therefore have projects involving quality management, projects that focus on production, projects involving our suppliers "	SM project have been defined together with different business functions	Cross-functional project teams to prepare implementation	
"In parallel to the definition of key project deliverables, we focus with our HR on current employees' competencies and how they should evolve... To spot possible gaps..."	HR included in the definition phase of SM projects		
"We set up our SM journey roadmap with the first priority of productivity – which is quite obvious."	Increasing productivity is main goal for SM projects	Identification of multiple strategic goals linked to SM	Management cognition/ dominant logic (MC)
"During our SM journey we realized that besides enhancing productivity, other objectives were within reach, so we included projects aimed at improving quality and enhancing our flexibility."	Enhancing quality and flexibility are additional strategic goals for SM projects		
"Our CEO is a technology enthusiast… His support, his commitment towards SM is valuable when you really need to change people's behavior. "	CEO is a technology enthusiast and facilitates change	Top management vision of technological future	
"Our CEO would have been the perfect one to explain you how it all started with Additive Manufacturing. He was the one who saw potential for AM in our field and propmpted us to conduct the first trials on serial production parts."	CEO was first to see potential for Additive Manufacturing		
"You need to present this projects to the workforce well in advance of the actual implementation…"	SM projects are to be introduced to workforce prior to implementation	Information diffusion about SM prior to project start	
"Then [when introducing SM projects] you need to thoroughly explain the goals of projects and then listen to workers, consider their feedback... This is an important topic which often gets dismissed..."	When introducing SM project is important to clarify goals and consider employees' feedback		

Data	1-st order indicators	2-nd order concepts	Theoretical themes
"Over the years I [CDO] have invested time and efforts to build a network of SM partners. It includes not only technology providers, but also universities, several startups..."	Network of SM partners developed by the CDO	CDO as boundary spanner	Individual knowledge development/sharing (KDC)
"My job [CDO] and the job of my team is to spot new trends early on in the market."	CDO in charge of spotting new trends		
"Concerning more mature production technologies, we mainly collaborate with traditional technology partners".	Collaborations with traditional technology partners concerning industry-specific SM application	Multiple collaborations with heterogenous technology partners	
"For developments wich are not solely dedicated to our industry we have several collaborations with startups. For example, we are currently working with some start-ups, especially in the field of Analytics for quality predictive purposes [...] We also need to find new ways of interacting with customers and on that we are working quite heavily with new startups."	Collaborations with startups on non industry-specific SM applications		
"We have also several different projects with universities, in fields in which the R&D component is especially relevant".	Collaborations with universities concerning explorative SM projects		
"We (senior management team) also spent one and a half years at an innovation incubator in San Francisco. We basically went there to learn how to work with startups. Not really to find a supplier, but to learn how they approach problems, how they solve problems..."	Senior managers learned how to work with startups	SM acculturation practices involving senior managers	
"Besides technical abilities tied to the use of new equipment, our employees needed to understand how analyze and manage data, how to react based on data…"	Technical abilities need to by corroborated by digital competences	Training to enhance digital competences	
"To support our employees' upskilling, we have created an app that they can use on their mobile devices. It offers trainings customized to their needs and current skill set"	Mobile app has been developed to provide employees with training to enhance digital competences		

Table 19: PAC/RAC: cross-case analysis (ref. Chapter 4)

Name	PAC		RAC	
	Summary	Degree	Summary	Degree
CoilsCo	Recognition of potential of SM dates back to mid-2000s. Regular SM market scanning with a focus on multiple SM technologies. Pioneering experimentation with AI for predictive quality. The R&D manager decomposes specialist SM knowledge into a form easy to be understood by non-experts. Distributed internal expertise on SM supports assimilation of SM knowledge in the fields of quality, logistics, production. Sound understanding of working principles of a wide range of SM technologies, including those not in use at the firms' sites (e.g. AI for industrial process control).	High	Development of an automated nonconformity identification system that meets firm's needs at lower costs than available solutions on the market. Co-development of an AI-based system to measure coils' properties in-line. Successful integration between legacy and new equipment. Continuous renewal of technological knowledge base deeply rooted in the firm's culture. Significant changes to working routines as employees' have transitioned from performing productive tasks to supervising operations and managing Big Data. Successful acceptance of change. All SM projects successfully completed. Patent obtained for AI-based system to measure coils' properties in-line. Use of SM knowledge as a source of competitive advantage mirrored by increase in market share.	High
PlasticCo	Early recognition of potential arising from interconnection of Cloud, IoT, Big Data to generate digital twins for presses. Regular SM market scanning with a focus on multiple SM technologies. Reliance on competencies of R&D manager to detect promising developments in SM and present them within the company. Distributed internal expertise on SM supports assimilation of SM knowledge in the fields of quality and logistics. Sound understanding of working principles of a broad range of SM technologies, including those not in use at the firms' sites (e.g. AM for serial production of parts).	High	Customization of several SM technologies (e.g. vertical integration technologies, automated nonconformities identification systems) to meet own needs. Ongoing co-development of a proprietary system that leverages on automation, Big Data, Analytics and AI to optimize process parameters in real-time. Successful integration between legacy and new equipment. Significant changes to working routines as employees' have transitioned from performing productive tasks to supervising operations and managing Big Data. Successful acceptance of change. All SM projects successfully completed. Use of SM knowledge to face market uncertainty	High
SinterCo	Early recognition of potential of SM. Regular SM market scanning with a focus on multiple technologies. Active search for common projects with customer firms. Pioneering experimentation with AM and Analytics applied to production data. Distributed internal expertise on SM supports assimilation of SM knowledge in the fields of quality and production. Employees have developed specific competences to work with external technology partners. Sound understanding of working principles of SM technologies, including those not in use at the firms' sites (e.g. AI for predictive quality).	High	Co-development of several, different SM applications (e.g. Big Data and Analytics, automated nonconformities identification systems, AM technology suited to firm's processes) to meet own needs. Successful integration between legacy and new equipment. Changes to the business model to integrate AM. Significant changes to working routines as employees' have transitioned from performing production tasks to being agile problem solvers. Successful acceptance of change. All SM projects successfully completed. Patent obtained for AM technology. Use of SM knowledge to respond to market uncertainty and gain competitive advantage.	High
StampingCo1	Regular SM market scanning limited to automation technologies. Use of Production Manager's competencies to assimilate specialist SM knowledge. Understanding of working principles of AM, although not currently in use at the firms' sites. No understanding of potential and working principles of more complex SM technologies, including Analytics and AI.	Medium	Purchase of standard SM solutions on the market. Successful integration between legacy and new equipment. Moderate changes to working routines arising from use of automation and digital interfaces. Successful acceptance of change. All SM projects successfully completed. Use of SM knowledge to respond to competitive pressure concerning cost.	Medium
WiresCo1	Regular SM market scanning limited to automation technologies. Use of Production Manager's specific competences to assimilate specialist SM knowledge. Clear understanding of potential and working principles of automation combined with vertical integration technologies and traceability technologies. No understanding of potential and working principles of more complex SM technologies, including AM, AI, Analytics.	Medium	Purchase of standard SM solutions on the market. Successful integration between legacy and new equipment. Moderate changes to working routines arising from use of automation and digital interfaces. Successful acceptance of change, after initial difficulties. All except one SM projects successfully completed. Use of SM knowledge to respond to competitive pressure concerning cost.	Medium
WiresCo2	Regular SM market scanning limited to automation and vertical integration technologies. Use of Production Manager's specific competences to decompose specialist SM knowledge. Understanding of working principles of traceability technologies and AM, although not currently in use at the firms' sites. No understanding of potential and working principles of more complex SM technologies, including AI, Big Data and Analytics.	Medium	Co-development of industrial robots suited to firm's processes. Successful integration between legacy and new equipment. Moderate changes to working routines arising from use of automation. Successful acceptance of change, after initial difficulties. All SM projects successfully completed. Use of SM knowledge has enabled response to competitive pressure concerning cost.	Medium
CastingCo1	Intermittent SM market scanning prompted by external customer pressures. Internal competences are not used to facilitate SM knowledge acquisition and assimilation. Understanding of working principles of SM technologies strictly limited to those in use at the firm's site.	Low	Purchase of standard SM solutions on the market. Moderate changes to working routines arising from use of automation. Workers' reluctance to embrace the change. Inability to quantify performance benefits arising from use of SM knowledge.	Low
CastingCo2	Intermittent market scanning. Internal competences are not used to facilitate SM knowledge acquisition and assimilation. Understanding of working principles of SM technologies strictly limited to those in use at the firm's site.	Low	Purchase of standard SM solutions on the market, although potential of co-developments is sensed. Deployment of new industrial robots slowed down by integration issues. Minimal changes to employees' working routines. Inability to quantify performance benefits arising from use of SM knowledge.	Low
GearsCo	Early recognition of potential of data sharing with customers. Regular SM market scanning limited to automation and vertical integration technologies. Use of COO's specific competences to decompose specialist knowledge concerning use of SM for predictive maintenance and occupational safety. Understanding of working principles of AM, although not currently in use at the firms' sites. No understanding of potential and working principles of AI and Analytics.	Medium	Purchase of standard SM solutions on the market. Minimal changes to employees' working routines. Inability to quantify performance benefits arising from use of SM knowledge.	Low
RubberCo	Recognition of SM potential at late stage and only as a result of technological constraints. Intermittent SM market scanning. Internal competences are not used to facilitate SM knowledge acquisition and assimilation. Understanding of working principles of SM technologies strictly limited to those in use at the firm's site.	Low	Purchase of standard SM solutions on the market. Challenging integration between legacy and new equipment. Minimal changes introduced to employees' working routines. Inability to quantify performance benefits arising from use of SM knowledge.	Low
StampingCo2	Deliberate avoidance of SM market scanning. Internal competences are not used to facilitate SM knowledge acquisition and assimilation. Understanding of working principles of SM technologies strictly limited to those in use at the firm's site.	Low	Several developments of automation solutions. Moderate changes to working routines arising from use of automation. Successful acceptance of change, after initial difficulties. Automation projects successfully completed. Use of SM knowledge to respond to competitive pressure concerning cost.	Medium
StampingCo3	Recognition of SM potential at late stage and only as a result of technological constraints. No regular market scanning. Internal competences are not used to facilitate SM knowledge acquisition and assimilation. Understanding of working principles of SM technologies strictly limited to those in use at the firm's site.	Low	Purchase of standard SM solutions on the market, deliberately preferred to customization or co-development of SM solutions. Minimal changes to employees' working routines. Inability to quantify performance benefits arising from use of SM knowledge.	Low

Table 20: Managerial antecedents supporting PAC (ref. Chapter 4)

			High PAC			Medium PAC				Low PAC				
			CoilsCo	PlasticCo	SinterCo	GearsCo	StampingCo1	WiresCo1	WiresCo2	CastingCo1	CastingCo 2	RubberCo	StampingCo2	StampingCo3
MC	Leadership	Identification of multiple strategic goals linked to SM	X	X	X									
		Identification of a clear strategic goal linked to SM				X	X	X	X	X				
		No clear strategic goals linked to SM									X	X	X	X
KDC	Gatekeepers or boundary spanners	R&D Managers/CDOs as boundary spanners	X	X	X									
		Production Manager as boundary spanner				X	X	X	X					
		No formal boundary spanning role assigned								X	X	X	X	X
	Openness to external collaborations	Multiple collaborations with diverse technology partners	X	X	X									
		Long-term collaborations with selected technology providers					X	X	X					
		Short-term or no collaborations with technology providers				X				X	X	X	X	X

Table 21: Managerial antecedents supporting RAC (ref. Chapter 4)

			High RAC			Medium RAC				Low RAC				
			CoilsCo	PlasticCo	SinterCo	StampingCo1	StampingCo2	WiresCo1	WiresCo2	CastingCo1	CastingCo 2	GearsCo	RubberCo	StampingCo3
CC	Adaptive and integrative capacities	Operational plans for SM projects	X	X	X									
		Routines to evaluate technological compatibility				X	X	X	X					
		No preliminary evaluation of technological compatibility								X	X	X	X	X
	Coordination capabilities	Cross-functional project teams to prepare implementation	X	X	X									
		No use of cross-functional project teams to prepare implementation				X	X	X	X	X	X	X	X	X
MC	Information provision by managers	Information sharing about goals of SM projects prior to implementation	X	X	X	X	X	X	X					
		Information sharing about goals of SM projects as a result of workers' requests after implementation started								X	X	X	X	X
	Leadership	Top management vision of technological future	X	X	X	X	X	X	X					
		Top management does not actively convey vision of technological future								X	X	X	X	X
KDC	Openness to external collaborations	Multiple collaborations with diverse technology partners	X	X	X									
	Training and employees' skills development/ transformation capabilities	Training to enhance digital competences	X	X	X									
		On-the-job technical skills training				X	X	X	X	X	X	X	X	X
		SM acculturation practices involving senior managers	X	X	X									
		No use of SM acculturation practices involving senior managers				X	X	X	X	X	X	X	X	X