The current issue and full text archive of this journal is available on Emerald Insight at:
https://www.emerald.com/insight/0144-3577.htm

The role of absorptive capacity in the adoption of Smart Manufacturing

Francesco Arcidiacono
Management and Business Engineering Research Group, Department of Electric, Electronic and Computer Engineering, University of Catania, Catania, Italy and Schaeffler Automotive Buehl, Buehl, Germany
Alessandro Ancarani and Carmela Di Mauro
Management and Business Engineering Research Group, Department of Civil Engineering and Architecture, University of Catania, Catania, Italy, and
Florian Schupp
Jacobs University Bremen, Bremen, Germany and Schaeffler Automotive Buehl, Buehl, Germany

Received 24 September 2021
Revised 3 February 2022
Accepted 10 March 2022

Abstract

Purpose – Smart Manufacturing (SM) lies at the core of Industry 4.0. Operations management research has identified several factors influencing firms' ability to adopt SM. However, a clear understanding of capabilities needed to progress in SM is still missing. This paper aims to investigate how absorptive capacity (AC) allows firms to advance in SM and explore how managerial antecedents support the capacity to absorb SM-related knowledge at different stages of SM adoption.

Design/methodology/approach – This study adopts an exploratory approach through multiple case studies. Twelve firms, operating as part of the automotive supply chain and exhibiting different stages of SM adoption, constitute the sample.

Findings – The results suggest that advancement in SM requires firms to progressively reinforce their AC. 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.

Originality/value – The findings contribute to SM research by suggesting that AC is a crucial dynamic capability for SM adoption. The results also provide evidence-grounded recommendations to firms engaged in the digital transformation on the managerial capabilities needed to support AC and to progress from lower to higher stages of SM.

Keywords Smart Manufacturing, Industry 4.0, Absorptive capacity, Multiple case study

Paper type Research paper

1. Introduction

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). Smart Manufacturing (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, 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

---

The present study was partially supported by a grant by University of Catania PIA.CE.RI. 2020-2022 Linea 2 - Progetto interdipartimentale GOSPEL.

International Journal of Operations & Production Management
Vol. 42 No. 6, 2022
pp. 773-796
© Emerald Publishing Limited
0144-3577
DOI 10.1108/IJOPM-09-2021-0615

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, to incorporate and exploit the potential 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 absorptive capacity (AC henceforth) (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 are 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 are still missing. To fill these gaps, this study addresses two research questions:

R1. How does absorptive capacity allow firms to progress to more advanced stages of Smart Manufacturing?

R2. 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, the 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.

The remainder of the study is organized as follows. Section 2 presents the background literature for the study, while Section 3 elaborates on the relevance of AC for SM. Section 4 explains the methodology, while Section 5 presents case study results. Finally, Section 6 discusses findings, Section 7 implications for research and practice and Section 8 concludes.

2. Background for the study

2.1 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 labeled 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 internet of things (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 organizational 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.

2.2 Absorptive capacity and its antecedents

Past research has shown that a key dynamic capability that supports technological innovation is represented by AC, 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, 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 characterized 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 and forward snowballing were performed until snowballing iterations failed to reveal articles not previously included (Table 1).

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 characterized 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, 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).

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

3. The role of absorptive capacity for Smart Manufacturing

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 and Mubarik, 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'

Table 1.
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)

boundaries and integrating it with the internal knowledge base. As argued in Section 2, 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 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, to progress in SM, firms may need to dynamically increase their knowledge absorption capacity. The process can be described as being characterized by iterative cycles (Todorova and Durisin, 2007), as illustrated in Figure 1. 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 support SM adoption in terms of knowledge

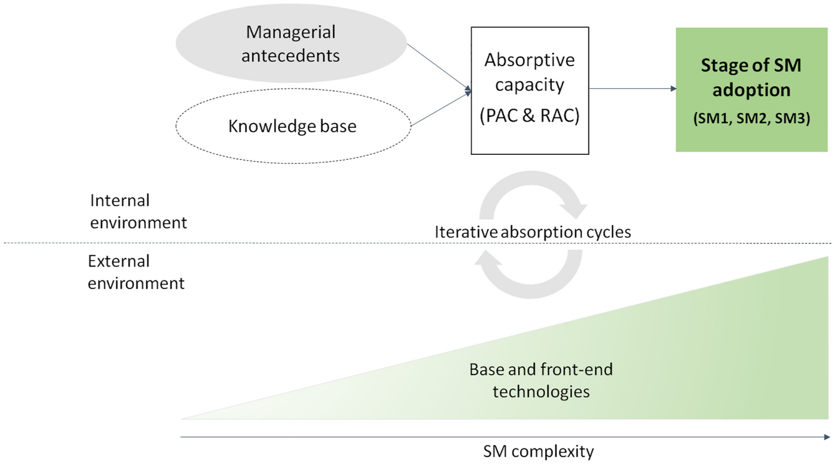

Figure 1.
An AC perspective on SM adoption

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).

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 (Barratt *et al.*, 2011).

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 analyzed. 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, 11 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 2), which enhances generalizability of findings (Eisenhardt and Graebner, 2007; Voss *et al.*, 2002).

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 2 h and were led by the plant manager and a technology manager, provided a robust understanding of SM technologies adopted at each site (Table 2) 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 as supplementary online material) 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 1). 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 min, 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).

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

Table 2. 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 – 6,500)	Manufacture of basic metals (Cold and hot rolling)	3 (plant manager, R&D manager, quality manager)	o Cloud o IoT o Big data o 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)	o Cloud o IoT o Big data o 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 - 6,600)	Manufacture of fabricated metal products (sintering)	4 (CEO, CDO, quality manager, production manager)	o Cloud o IoT o Big data o 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)	o Cloud o IoT o 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 and production manager)	o Cloud o IoT o Big data	a. Industrial robots b. PLCs + sensors + actuators, SCADA, MES, ERP c. Energy management d. Traceability of raw materials/final products
	WiresCo2 (large - 1,400)	Manufacture of fabricated metal products (wire drawing)	2 (CEO, production manager)	o Cloud o IoT o Big data	a. Automated nonconformities identification, industrial robots b. PLCs + sensors + actuators, SCADA, MES, ERP c. Energy management

(*continued*)

Table 2.

	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)
SM1	CastingCo1 (large –600)	Manufacture of basic metals (iron casting)	3 (CEO, CDO, sales manager)	o 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)	o 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)	o 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)	o 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)	o Cloud	a. Automated nonconformities identification, industrial robots b. PLCs + sensors + actuators, ERP
	StampingCo3 (medium - 240)	Manufacture of fabricated metal products (metal forming)	3 (HR and IT manager, quality manager, sales manager)	o Cloud	a. Automated nonconformities identification, industrial robots b. PLCs + sensors + actuators, ERP

particular, the two researchers independently analyzed 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 labeled with first-order indicators. Indicators were allowed to emerge until the analysis failed to reveal new ones. Next, indicators were organized into higher-level (second-order) concepts. At this stage, AC literature and SM literature 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 as supplementary online material (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 2).

Next, 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 (supplementary online material – 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, 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 (supplementary online material – Tables C and 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.

5. Findings

5.1 Potential absorptive capacity, realized absorptive capacity and stage of Smart Manufacturing adoption

The qualitative cross-case analysis was used to explore how the degree of PAC and RAC is related to the SM stage. Table 3 summarizes the 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

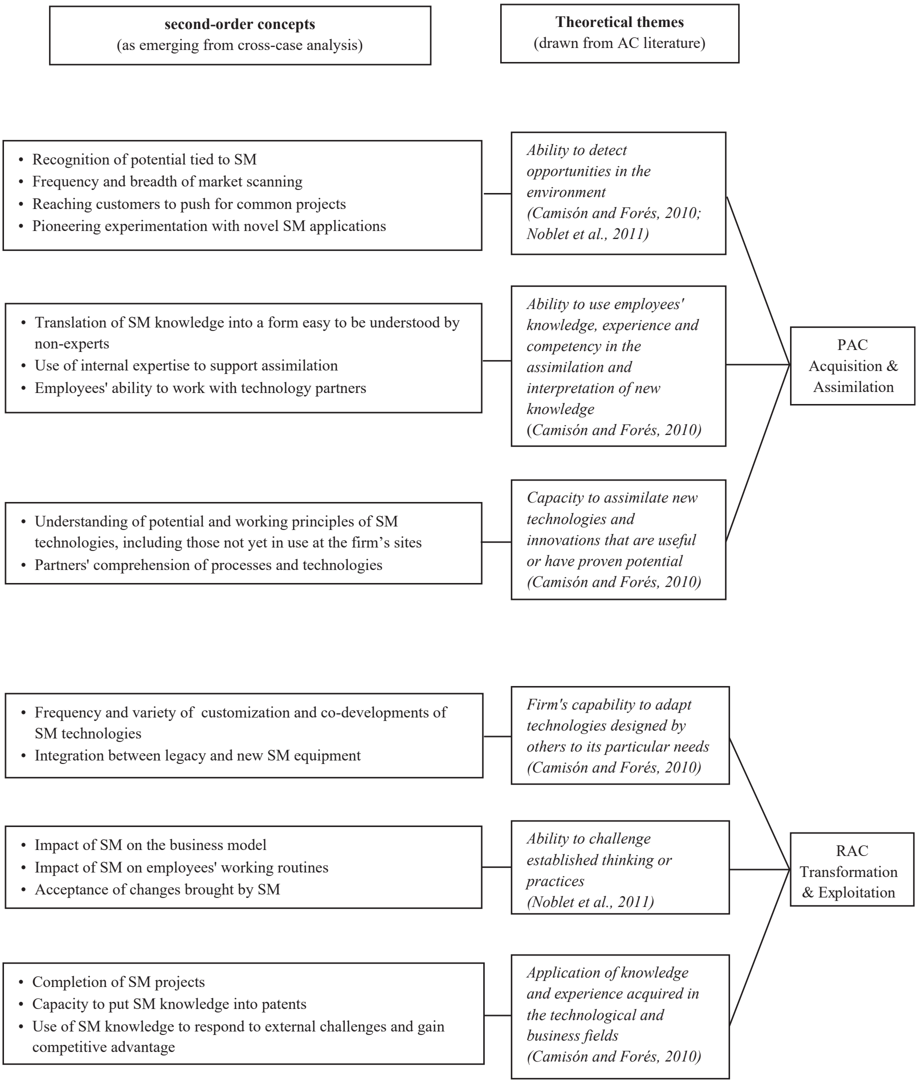

Figure 2.
PAC/RAC: second-order concepts and theoretical themes

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, to assimilate technological knowledge and

Table 3. PAC/RAC and stage of SM adoption: contingency table

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

envision applications, SM2 firms 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.

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.*"

The findings also highlight that 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.*"

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, 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 toward 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.

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 3 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.

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.

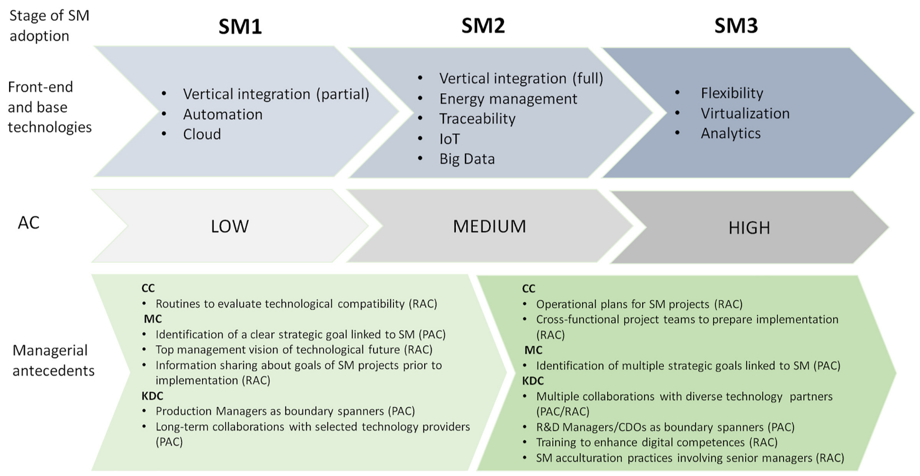

Figure 3.
Managerial antecedents supporting SM knowledge absorption

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 proactively 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 a 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, the 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 to achieve successful SM adoption and suggesting research opportunities in the exploration of manufacturing strategies and digitalization.

With respect to KDC, the 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 centers (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 toward 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), the 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).

The findings also point that MC is a relevant antecedent of RAC through information provision to subordinates and socialization capabilities. Specifically, irrespective of SM advancement, the findings confirm the criticality of effective management communication capabilities to challenge existing practices and expedite alignment to required behaviors (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, the 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.

7. Research and managerial implications

This study responds to calls for expanding empirical research on Industry 4.0 (Koh *et al.*, 2019) and contributes to the operations management literature on the adoption of Industry 4.0 technologies in two main ways. First, it enriches the body of evidence 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) by offering evidence of the relevance of AC for SM adoption. In particular, the study provides an analysis of how AC evolves to enable more advanced SM stages.

Second, as discussed in the previous section, the findings emphasize that SM knowledge absorption builds on a set of antecedents, the role of some of which 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 AC 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).

The findings also offer three main implications for practice. First, the study provides guidance to business leaders interested in the SM transformation by highlighting how managerial capabilities need to be developed or enhanced to support SM progression. In particular, the results point to the relevance of KDC 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. The findings also highlight the importance of CC, which call for creating routines aimed at facilitating integration of new SM equipment with existing configurations of equipment, and of MC, as exemplified by practices oriented at involving employees in the process of change at early stages.

Next, case evidence highlights the progressive nature of firms' SM transformation, in line with the tenets of AC 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.

Finally, the findings point to the need of a progressive change in firms' mind-sets. For instance, the transition from SM1 to SM3 means overcoming distrust towards external collaborations and shifting first to selected collaborations where trust prevails (SM2) and then to a wider network where the risk of openness is deemed to be more than offset by the benefits (SM3).

8. Conclusions and limitations

The emergence of the SM paradigm calls organizations to innovate their processes by progressively integrating increasingly complex blocks of technological endowments. This study has interpreted SM adoption as a knowledge accumulation process enabled by a firm's AC. The findings suggest that SM progression requires firms' AC to co-evolve, as firms are called to gradually increase their ability to proactively search technological opportunities and to use internal expertise to assimilate and exploit complex SM knowledge. Managerial antecedents, in the forms of CC, MC and KDC, differently support knowledge absorption as firms progress in SM.

Limitations of this study should be acknowledged. First, since the study does not include firms that have not implemented any form of SM, future research should investigate whether low degrees of PAC/RAC constitute a necessary condition for SM1. Second, the study is carried out on a sample of firms facing 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. Next, our analysis has focused on intra-firm antecedents, neglecting supply chain characteristics and the external environment. Further, case study analysis of SM adoption could be complemented by other methodologies such as system dynamics to study the cycles of SM knowledge accumulation. More in general, further research is needed to throw light on the dynamic capabilities supporting the digital transformation.

References

Adner, R. and Helfat, C.E. (2003), "Corporate effects and dynamic managerial capabilities", *Strategic Management Journal*, Vol. 24 No. 10, pp. 1011-1025.

Ancarani, A., Di Mauro, C., Legenvre, H. and Cardella, M. (2019), "Internet of things adoption: a typology of projects", *International Journal of Operations and Production Management*, Vol. 40 No. 6, pp. 849-872.

Arcidiacono, F., Ancarani, A., Di Mauro, C. and Schupp, F. (2019), "Where the rubber meets the road. Industry 4.0 among SMEs in the automotive sector", *IEEE Engineering Management*, Vol. 47 No. 4, pp. 86-93.

Barratt, M., Choi, T.Y. and Li, M. (2011), "Qualitative case studies in operations management: trends, research outcomes, and future research implications", *Journal of Operations Management*, Vol. 29 No. 4, pp. 329-342.

Benitez, G.B., Ayala, N.F. and Frank, A.G. (2020), "Industry 4.0 innovation ecosystems: an evolutionary perspective on value cocreation", *International Journal of Production Economics*, Vol. 228, p. 107735.

Bluhm, D.J., Harman, W., Lee, T.W. and Mitchell, T.R. (2011), "Qualitative research in management: a decade of progress", *Journal of Management Studies*, Vol. 48 No. 8, pp. 1866-1891.

Bouguerra, A., Mellahi, K., Glaister, K., Hughes, M. and Tatoglu, E. (2021), "Revisiting the concept of absorptive capacity: the moderating effects of market sensing and responsiveness", *British Journal of Management*, Vol. 32 No. 2, pp. 342-362.

Brettel, M., Friederichsen, N., Keller, M. and Rosenberg, N. (2014), "How virtualization, decentralization and network building change the manufacturing landscape: an Industry 4.0 perspective", *International Journal of Science, Engineering and Technology*, Vol. 8 No. 1, pp. 37-44.

Cagliano, R., Canterino, F., Longoni, A. and Bartezzaghi, E. (2019), "The interplay between smart manufacturing technologies and work organization: the role of technological complexity", *International Journal of Operations and Production Management*, Vol. 39 Nos 6/7/8, pp. 913-934.

Camisón, C. and Forés, B. (2010), "Knowledge absorptive capacity: new insights for its conceptualization and measurement", *Journal of Business Research*, Vol. 63 No. 7, pp. 707-715.

Chen, D.Q., Preston, D.S. and Swink, M. (2015), "How the use of big data analytics affects value creation in supply chain management", *Journal of Management Information Systems*, Vol. 32 No. 4, pp. 4-39.

Cohen, W. and Levinthal, D. (1990), "Absorptive capacity: a new perspective on learning and innovation", *Administrative Science Quarterly*, Vol. 35 No. 1, pp. 128-152.

Culot, G., Nassimbeni, G., Orzes, G. and Sartor, M. (2020), "Behind the definition of Industry 4.0: analysis and open questions", *International Journal of Production Economics*, Vol. 226, p. 107617.

Dalenogare, L.S., Benitez, G.B., Ayala, N.F. and Frank, A.G. (2018), "The expected contribution of Industry 4.0 technologies for industrial performance", *International Journal of Production Economics*, Vol. 204, pp. 383-394.

de Araújo Burcharth, A.L.L., Lettl, C. and Ulhøi, J.P. (2015), "Extending organizational antecedents of absorptive capacity: organizational characteristics that encourage experimentation", *Technological Forecasting and Social Change*, Vol. 90, pp. 269-284.

Delic, M. and Eyers, D.R. (2020), "The effect of additive manufacturing adoption on supply chain flexibility and performance: an empirical analysis from the automotive industry", *International Journal of Production Economics*, Vol. 228, p. 107689.

Dijksterhuis, M.S., Van den Bosch, F.A.J. and Volberda, H.W. (1999), "Where do new organizational forms come from? Management logics as a source of coevolution", *Organization Science*, Vol. 10 No. 5, pp. 569-582.

Eisenhardt, K.M. (1989), "Building theories from case study research", *Academy of Management Review*, Vol. 14 No. 4, pp. 532-550.

Eisenhardt, K.M. and Graebner, M.E. (2007), "Building from cases: opportunities and challenges", *Academy of Management Journal*, Vol. 50 No. 1, pp. 25-32.

Eyers, D.R., Potter, A.T., Gosling, J. and Naim, M.M. (2018), "The flexibility of industrial additive manufacturing systems", *International Journal of Operations and Production Management*, Vol. 38 No. 12, pp. 2313-2343.

Flatten, T., Adams, D. and Brettel, M. (2015), "Fostering absorptive capacity through leadership: a cross-cultural analysis", *Journal of World Business*, Vol. 50 No. 3, pp. 519-534.

Fleiss, J.L. (1971), "Measuring nominal scale agreement among many raters", *Psychological Bulletin*, Vol. 76 No. 5, pp. 378-382.

Fosfuri, A. and Tribó, J. (2008), "Exploring the antecedents of potential absorptive capacity and its impact on innovation performance", *Omega*, Vol. 36 No. 2, pp. 173-187.

Frank, A.G., Dalenogare, L.S. and Ayala, N.S. (2019), "Industry 4.0 technologies: implementation patterns in manufacturing companies", *International Journal of Production Economics*, Vol. 210, pp. 15-26.

Garrety, K., Robertson, P.L. and Badham, R. (2004), "Integrating communities of practice in technology development projects", *International Journal of Project Management*, Vol. 22 No. 5, pp. 351-358.

Gioia, D.A., Corley, K.G. and Hamilton, A.L. (2013), "Seeking qualitative rigor in inductive research: notes on the Gioia methodology", *Organizational Research Methods*, Vol. 16 No. 1, pp. 15-31.

Gomez, J. and Vargas, P. (2009), "The effect of financial constraints, absorptive capacity and complementarities on the adoption of multiple process technologies", *Research Policy*, Vol. 38 No. 1, pp. 106-119.

Helfat, C.E. and Martin, J.A. (2015), "Dynamic managerial capabilities: review and assessment of managerial impact on strategic change", *Journal of Management*, Vol. 41 No. 5, pp. 1281-1312.

Helfat, C.E. and Raubitschek, R.S. (2018), "Dynamic and integrative capabilities for profiting from innovation in digital platform-based ecosystems", *Research Policy*, Vol. 47 No. 8, pp. 1391-1399.

Hofmann, E. and Rüsch, M. (2017), "Industry 4.0 and the current status as well as future prospects on logistics", *Computers in Industry*, Vol. 89, pp. 23-34.

Horváth, D. and Szabó, R. (2019), "Driving forces and barriers of Industry 4.0: do multinational and small and medium-sized companies have equal opportunities?", *Technological Forecasting and Social Change*, Vol. 146, pp. 119-132.

Jansen, J., Van Den Bosch, F. and Volberda, H.W. (2005), "Managing potential and realized absorptive capacity: how do organizational antecedents matter?", *Academy of Management Journal*, Vol. 48 No. 6, pp. 999-1015.

Jaskò, S., Skrop, A., Holczinger, T., Chován, T. and Abonyi, J. (2020), "Development of manufacturing execution systems in accordance with Industry 4.0 requirements: a review of standard- and ontology-based methodologies and tools", *Computers in Industry*, Vol. 123, p. 103300.

Kagermann, H., Wahlster, W. and Helbig, J. (2013), *Recommendations for Implementing the Strategic Initiative INDUSTRIE 4.0. Final Report of the Industrie 4.0 Working Group*, available at: https://en.acatech.de/publication/recommendations-for-implementing-the-strategic-initiative-industrie-4-0-final-report-of-the-industrie-4-0-working-group/ (accessed 02 February 2022).

Kamble, S.S., Gunasekaran, A., Ghadge, A. and Raut, R. (2020a), "A performance measurement system for industry 4.0 enabled smart manufacturing system in SMMEs-A review and empirical investigation", *International Journal of Production Economics*, Vol. 229, p. 107853.

Kamble, S.S., Gunasekaran, A. and Dhone, N.C. (2020b), "Industry 4.0 and lean manufacturing practices for sustainable organisational performance in Indian manufacturing companies", *International Journal of Production Research*, Vol. 58 No. 5, pp. 1319-1337.

Kane, G., Palmer, D., Phillips, A.N., Kiron, D. and Buckley, N. (2016), "Aligning the organisation for its digital future", available at: https://sloanreview.mit.edu/projects/aligning-for-digital-future/ (accessed 02 February 2022).

Kogut, B. and Zander, U. (1992), "Knowledge of the firm, combinative capabilities, and the replication of technology", *Organization Science*, Vol. 3 No. 3, pp. 383-397.

Koh, L., Orzes, G. and Jia, F. (2019), "The fourth industrial revolution (Industry 4.0) technologies' disruption on operations and supply chain management", *International Journal of Operations and Production Management*, Vol. 39 Nos 6/7/8, pp. 817-828.

Lane, P.J., Salk, J.E. and Lyles, M.A. (2001), "Absorptive capacity, learning, and performance in international joint ventures", *Strategic Management Journal*, Vol. 22 No. 1, pp. 1139-1161.

Laursen, K. and Salter, A. (2006), "Open for innovation: the role of openness in explaining innovation performance among UK manufacturing firms", *Strategic Management Journal*, Vol. 27 No. 2, pp. 131-150.

Lenox, M. and King, A. (2004), "Prospects for developing absorptive capacity through internal information provision", *Strategic Management Journal*, Vol. 25 No. 4, pp. 331-345.

Li, C., Sun, L.-Y. and Dong, Y. (2018), "Innovating via building absorptive capacity: interactive effects of top management support of learning, employee learning orientation and decentralization structure", *Creativity and Innovation Management*, Vol. 27 No. 4, pp. 431-443.

Lin, H.-F. (2014), "Understanding the determinants of electronic supply chain management system adoption: using the technology–organization–environment framework", *Technological Forecasting and Social Change*, Vol. 86, pp. 80-92.

Lin, D., Lee, C.K., Lau, H. and Yang, Y. (2018), "Strategic response to Industry 4.0: an empirical investigation on the Chinese automotive industry", *Industrial Management and Data Systems*, Vol. 118 No. 3, pp. 589-605.

Lorenz, R., Benninghaus, C., Friedli, T. and Netland, T.H. (2020), "Digitization of manufacturing: the role of external search", *International Journal of Operations and Production Management*, Vol. 40 Nos 7/8, pp. 1129-1152.

Mahmood, T. and Mubarik, M.S. (2020), "Balancing innovation and exploitation in the fourth industrial revolution: role of intellectual capital and technology absorptive capacity", *Technological Forecasting and Social Change*, Vol. 160, p. 120248.

Mero-Jaffe, I. (2011), "'Is that what I said?' interview transcript approval by participants: an aspect of ethics in qualitative research", *International Journal of Qualitative Methods*, Vol. 10 No. 3, pp. 231-247.

Miles, M.B., Huberman, A.M. and Saldaña, J. (2013), *Qualitative Data Analysis: A Methods Sourcebook*, 3rd ed., Sage Publications, Thousand Oaks.

Miller, C.C., Cardinal, L.B. and Glick, W.H. (1997), "Retrospective reports in organizational research: a reexamination of recent evidence", *Academy of Management Journal*, Vol. 40 No. 1, pp. 189-204.

Mittal, S., Khan, M.A., Romero, D. and Wuest, T. (2018), "A critical review of smart manufacturing and Industry 4.0 maturity models: implications for small and medium-sized enterprises (SMEs)", *Journal of Manufacturing Systems*, Vol. 49, pp. 194-214.

Moeuf, A., Pellerin, R., Lamouri, S., Tamayo-Giraldo, S. and Barbaray, R. (2018), "The industrial management of SMEs in the era of Industry 4.0", *International Journal of Production Research*, Vol. 56 No. 3, pp. 1118-1136.

Moeuf, A., Lamouri, S., Pellerin, R., Tamayo-Giraldo, S., Tobon-Valencia, E. and Eburdy, R. (2020), "Identification of critical success factors, risks and opportunities of Industry 4.0 in SMEs", *International Journal of Production Research*, Vol. 58 No. 5, pp. 1384-1400.

Müller, J.M., Buliga, O. and Voigt, K.I. (2021), "The role of absorptive capacity and innovation strategy in the design of industry 4.0 business Models-A comparison between SMEs and large enterprises", *European Management Journal*, Vol. 39 No. 3, pp. 333-343.

Noblet, J.P., Simon, E. and Parent, R. (2011), "Absorptive capacity: a proposed operationalization", *Knowledge Management Research and Practice*, Vol. 9, pp. 367-377.

Omidvar, O., Edler, J. and Malik, K. (2017), "Development of absorptive capacity over time and across boundaries: the case of RD consortia", *Long Range Planning*, Vol. 50 No. 5, pp. 665-683.

Raj, A., Dwivedi, G., Sharma, A., de Sousa Jabbour, A.B.L. and Rajak, S. (2020), "Barriers to the adoption of industry 4.0 technologies in the manufacturing sector: an inter-country comparative perspective", *International Journal of Production Economics*, Vol. 224, p. 107546.

Ricci, R., Battaglia, D. and Neirotti, P. (2021), "External knowledge search, opportunity recognition and industry 4.0 adoption in SMEs", *International Journal of Production Economics*, Vol. 240, p. 108234.

Robertson, P.L., Casali, G.L. and Jacobson, D. (2012), "Managing open incremental process innovation: absorptive Capacity and distributed learning", *Research Policy*, Vol. 41 No. 5, pp. 822-832.

Sailer, P., Stutzmann, B. and Kobold, L. (2019), "Successful digital transformation –how change management helps you to hold course", available at: https://assets.new.siemens.com/siemens/assets/api/uuid:103ce0a5-2f0b-45d7-837c- (accessed 02 February 2022).

Seyedghorban, Z., Samson, D. and Tahernejad, H. (2020), "Digitalization opportunities for the procurement function: pathways to maturity", *International Journal of Operations and Production Management*, Vol. 40 No. 11, pp. 1685-1693.

Sony, M. and Naik, S. (2020), "Critical factors for the successful implementation of Industry 4.0: a review and future research direction", *Production Planning and Control*, Vol. 31 No. 10, pp. 799-815.

Sousa-Zomer, T.T., Neely, A. and Martinez, V. (2020), "Digital transforming capability and performance: a microfoundational perspective", *International Journal of Operations and Production Management*, Vol. 40 Nos 7/8, pp. 1095-1128.

Spithoven, A., Clarysse, B. and Knockaert, M. (2010), "Building absorptive capacity to organise inbound open innovation in traditional industries", *Technovation*, Vol. 30 No. 2, pp. 130-141.

Su, H.C., Linderman, K., Schroeder, R.G. and Van de Ven, A.H. (2014), "A comparative case study of sustaining quality as a competitive advantage", *Journal of Operations Management*, Vol. 32 Nos 7/8, pp. 429-445.

Tao, F., Qi, Q., Liu, A. and Kusiak, A. (2018), "Data-driven smart manufacturing", *Journal of Manufacturing Systems*, Vol. 48, pp. 157-169.

Teece, D.J. (2007), "Explicating dynamic capabilities: the nature and microfoundations of (sustainable) enterprise performance", *Strategic Management Journal*, Vol. 28 No. 13, pp. 1319-1350.

Todorova, G. and Durisin, B. (2007), "Absorptive capacity: valuing a reconceptualization", *Academy of Management Review*, Vol. 32 No. 3, pp. 774-786.

Tortorella, G.L., Giglio, R. and van Dun, D.H. (2019), "Industry 4.0 adoption as a moderator of the impact of lean production practices on operational performance improvement", *International Journal of Operations and Production Management*, Vol. 39 Nos 6/7/8, pp. 860-886.

Tortorella, G.L., Vergara, A.M.C., Garza-Reyes, J.A. and Sawhney, R. (2020), "Organizational learning paths based upon industry 4.0 adoption: an empirical study with Brazilian manufacturers", *International Journal of Production Economics*, Vol. 219, pp. 284-294.

Tsai, K.H. (2009), "Collaborative networks and product innovation performance: toward a contingency perspective", *Research Policy*, Vol. 38 No. 5, pp. 765-778.

Tumbas, S., Berente, N. and Brocke, J.V. (2018), "Digital innovation and institutional entrepreneurship: chief digital officer perspectives of their emerging role", *Journal of Information Technology*, Vol. 33 No. 3, pp. 188-202.

Volberda, H.W. (1996), "Toward the flexible form: how to remain vital in hypercompetitive environments", *Organization Science*, Vol. 7 No. 4, pp. 359-387.

Volberda, H.W., Foss, N.J. and Lyles, M.A. (2010), "Absorbing the concept of absorptive capacity: how to realize its potential in the organization field", *Organization Science*, Vol. 21 No. 4, pp. 931-951.

Voss, C., Tsikriktsis, N. and Frohlich, M. (2002), "Case research in operations management", *International Journal of Operations and Production Management*, Vol. 22 No. 2, pp. 195-219.

Wamba, F.S., Gunasekaran, A., Akter, S., Ren, S.J., Dubey, R. and Childe, S.J. (2017), "Big data analytics and firm performance: effects of dynamic capabilities", *Journal of Business Research*, Vol. 70, pp. 356-365.

Wang, L., Zhao, J.Z. and Zhou, K.Z. (2018), "How do incentives motivate absorptive capacity development? The mediating role of employee learning and relational contingencies", *Journal of Business Research*, Vol. 85, pp. 226-237.

Warner, K.S. and Wäger, M. (2019), "Building dynamic capabilities for digital transformation: an ongoing process of strategic renewal", *Long Range Planning*, Vol. 52 No. 3, pp. 326-349.

Xia, T. and Roper, S. (2008), "From capability to connectivity—absorptive capacity and exploratory alliances in biopharmaceutical firms: a US–Europe comparison", *Technovation*, Vol. 28 No. 11, pp. 776-785.

Xu, L.D., Xu, E.L. and Li, L. (2018), "Industry 4.0: state of the art and future trends", *International Journal of Production Research*, Vol. 56 No. 8, pp. 2941-2962.

Yin, R.K. (1994), *Case Study Research: Design and Methods*, 2nd ed., Sage Publications, Thousand Oaks.

Zahra, S.A. and George, G. (2002), "Absorptive capacity: a review, reconceptualization, and extension", *Academy of Management Review*, Vol. 27 No. 2, pp. 185-203.

Zhang, M., Zhao, X. and Lyles, M. (2018), "Effects of absorptive capacity, trust and information systems on product innovation", *International Journal of Operations and Production Management*, Vol. 38 No. 2, pp. 493-512.

Zheng, T., Ardolino, M., Bacchetti, A., Perona, M. and Zanardini, M. (2019), "The impacts of Industry 4.0: a descriptive survey in the Italian manufacturing sector", *Journal of Manufacturing Technology Management*, Vol. 31 No. 5, pp. 1085-1115.

Appendix

The supplementary file is available online for this article at: https://drive.google.com/file/d/1GN6hspvNmlRkRvFFiSPXPjAwf1jDPgDe/view?usp=sharing

Corresponding author
Francesco Arcidiacono can be contacted at: francesco.arcidiacono@phd.unict.it

For instructions on how to order reprints of this article, please visit our website:
www.emeraldgrouppublishing.com/licensing/reprints.htm
Or contact us for further details: **permissions@emeraldinsight.com**