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Disentangling the link between ICT and Industry 4.0: impacts on knowledge-related performance

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Abstract

Purpose – Industry 4.0 technologies are promising to increase manufacturing companies' performance through the new knowledge that such digital technologies allow to create and manage within the firm boundaries and through customer interactions. Despite the great attention on the Industry 4.0 adoption paths, little is known about the relationships with previous waves of digital technologies, namely, information and communication technologies (ICTs), and how different groups of both types of technologies link to knowledge and its related performances.

Design/methodology/approach – The study employed a quantitative research design using a survey method. Submitting the questionnaire to entrepreneurs, chief operation officers or managers in charge of the operational and technological processes of Italian manufacturing firms, 206 respondents stated that their firm has adopted at least one of the seven Industry 4.0 technologies investigated.

Findings – The findings of the study highlight the positive relationship between ICT and Industry 4.0 technologies in terms of both intensity and groups of technologies (Web-based, Management and Manufacturing ICT; Operation, Customization and Data-processing 4.0), and how technologies affect knowledge-related performances in terms of products and processes, job-learning, product-related services and customer involvement.

Originality/value – This study is one of the first attempts to link groups of ICT to groups of Industry 4.0 technologies and to explore the effects in terms of knowledge-related performances as a measure of technology use. The study shows strong path dependency among ICT, Industry 4.0 and knowledge performance, enriching the literature on technological innovation and knowledge management.

Keywords Industry 4.0, Digital transformation, ICT, Manufacturing firms, Knowledge-related performance

Paper type Research paper

1. Introduction

There is a growing attention on how new emerging technologies – from 3D printing to advanced robotics, from Internet of Things (IoT) to big data and analytics – are enabling the rise of the digital transformation, known as Industry 4.0 (Galati and Bagliardi, 2019). Specifically, to compete successfully, manufacturing firms need extensive digital connectivity between manufacturing processes and other business areas through the adoption of several different technologies (Ghobakhloo, 2018) that could follow a previous technological strategy (Kane *et al.*, 2015b), and thus previous investment in information and communication technologies (ICTs) (Ghobakhloo and Fathi, 2020).

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Although Industry 4.0 encompasses a large set of technologies, recent literature showed the possibility to group them into main categories, taking into consideration the use and the impacts on business processes (Zheng *et al.*, 2021), such as technologies for operations, for improvement of customization processes and for data exploitation (Culot *et al.*, 2020a; Frank *et al.*, 2019a). Similarly, for ICT, past research has highlighted three main technological waves linked to different applications in business processes: to manage information, to organize production processes or activities and to interact with markets and customers (Wang *et al.*, 2007).

Given the positive link between ICT investment and Industry 4.0, further research is needed to disentangle the connections within these different groups. Therefore, the first aim of this study is to assess the relationships between groups of ICT and Industry 4.0 technologies to advance literature on Industry 4.0 implementation paths based on previous technological investments.

Literature highlights that technological revolutions positively impact not only operations and other business processes but also the way organizations measure and manage performance, stressing the key role of knowledge (Sardi *et al.*, 2019) for strategic purposes (Bettiol *et al.*, 2020a). ICT and Industry 4.0 technologies can positively affect, through the creation of new knowledge, improvements in the production process, the development of new competences, the development of new products and services and improvement in the customization process and in customer engagement (Capestro and Kinkel, 2020; Mithas *et al.*, 2011). Despite the relevance of ICT and Industry 4.0 for knowledge management (Roblek *et al.*, 2016; Sambamurthy and Subramani, 2005), limited attention has been given to understanding relationships between investment first in ICT and then in Industry 4.0, in terms of groups of specific of technologies and knowledge-related performance. The relevance of knowledge and its effective management within the new technological scenario requires to better consider those implications within the performance measure and management system of adopters (Sahlin and Angelis, 2019). In this regard, the second aim of this study is to assess how groups of both ICT and Industry 4.0 technologies affect knowledge-related performances meant as improvements in business process through new knowledge created with the use of technologies (Wang *et al.*, 2007). In this way, the paper aims at enriching literature on relationships between knowledge performance and technology use in firms.

Based on a sample of 206 Italian manufacturing firms, results show a positive relation between the intensity of ICT and Industry 4.0 (in terms of number of technologies), as well as between specific groups of ICT (Web-based ICT, Management ICT and Manufacturing ICT) and Industry 4.0 technologies (Operation 4.0, Customization 4.0 and Data-processing 4.0). Moreover, it emerges that mainly Operation 4.0 technologies and Manufacturing ICT allow improvements in terms of new knowledge creation, development of new competences and product-related services, and enhancement of customer engagement in new product development process. Instead, the use of Data-processing 4.0 technologies is particularly important for developing product-related services.

The paper is structured as follows: in section 2, we present the theoretical background. In section 3, we detail the methodology. In section 4, we report the results of the analysis. In section 5, we discuss results. Finally, in section 6, we outline the conclusions, the theoretical and managerial implications, and suggestions regarding limitations and future research.

2. Theoretical background

2.1 Industry 4.0 technologies and related business implications

A growing body of literature is discussing the opportunities and challenges of Industry 4.0 (Liao *et al.*, 2017) that aims at enhancing the firm's competitiveness by integrating information technologies into the manufacturing processes to quickly adapt production and products to market changes (Wagire *et al.*, 2019). This new technological paradigm involves a new intelligent, autonomous and flexible smart manufacturing system as a new production approach that relies on the adoption of different enabling technologies (e.g. Alcácer and Cruz-Machado, 2019; Oztemel and Gursev, 2020; Tortorella and Fettermann, 2017) that are progressively redefining manufacturing and managerial processes (Saucedo-Martinez *et al.*, 2017). Literature on performance measurement and management (Nudurupati *et al.*, 2016) emphasizes both the opportunities and challenges of the digital technological scenario, connected to the huge amount of data that the different technologies allow to gather and manage and linked to the new knowledge firms may create to face the dynamic and complex competitive environment (Del Vecchio *et al.*, 2018).

Scholars recently have showed that such technologies could be grouped into main clusters based on the use and the impacts of the different technologies on business and manufacturing processes (Zheng *et al.*, 2021). Although different clusters emerged (Culot *et al.*, 2020a; Frank *et al.*, 2019a), the adoption of Industry 4.0 technologies by manufacturing industries (Zheng *et al.*, 2019) could follow three main directions strictly related to the main improvements linked to the concept of smart factory (Jung *et al.*, 2021), that technolgies allow to ahcieve: (1) efficiency and productivity, (2) flexibility and customization and (3) data processing.

The first direction concerns the Industry 4.0 technologies adopted to improve operations and working activities to enhance productivity and production efficiency. Studies showed robotics (advanced, autonomous, collaborative) is the main technology used for these purposes (Ghobakhloo, 2018; Frank *et al.*, 2019a; Zheng *et al.*, 2021). In addition to robotics, scholars considered other possible technologies adopted for operations activities, such as augmented/virtual reality that aims at supporting workers during operations activities (Scurati *et al.*, 2018), as well as additive manufacturing applied for the production of complex products (Baumers *et al.*, 2016).

The second direction considers technologies for flexibility and customization purposes (Weller *et al.*, 2015). Manufacturing firms can implement additive manufacturing technologies, and, specifically, 3D printing, which is the most suitable for that purposes (D’Aveni, 2015). In addition, studies comprise other technologies in this possible cluster, such as flexible machineries and tools to support digital manufacturing (Tong *et al.*, 2020), as well as robotics (Culot *et al.*, 2020a). The former are more suitable for customization purposes (Kusiak, 2018), and the latter mainly for flexibility (Wang *et al.*, 2017). However, the synergic integration of such technologies aims at developing new reconfigurable solutions for flexible customized processes and products (He and Bai, 2021), with positive effects on customer involvement in joint innovation and co-creation activities (Rayna and Striukova, 2016).

The third direction is rooted in data exploitation and the chance to enhance information management via, among others, cloud, big data analysis and IoT solutions (Klingenberg *et al.*, 2021). Scholars referred to this group of technologies as *base technologies* that provide connectivity and intelligence with benefits in all different business areas (Frank *et al.*, 2019a) or *data-processing technologies* useful for providing information-driven input that improves decision-making processes (Culot *et al.*, 2020a). This cluster of technologies influences the production and marketing spheres (Tao *et al.*, 2018), as they enable firms to profile customers and offer them customized products (Coreynen *et al.*, 2017) and services (Frank *et al.*, 2019b).

The main implications related to the adoption of new technologies emphasize the relevant of Industry 4.0 for manufacturers’ transformation, opening up new potentialities in terms of how performances are measured and business processes are managed in the competitive context of the fourth industrial revolution (Kamble *et al.*, 2020). However, despite the discussion on the present technological scenario as a new radical paradigm, past research on the adoption of ICT and the effects on business processes show their relevance for production activities, the management of both internal processes and interactions with external actors, both suppliers and customers (Barba-Sánchez *et al.*, 2007). In this regard, we are interested in further exploring the links between Industry 4.0 and the previous technology waves, and its implications within the performance measurement and management framework by specifically adopting a knowledge perspective (knowledge as a key resource of the firm) (Aboelmaged, 2014; Bourne *et al.*, 2018; Franco-Santos *et al.*, 2012). Although researchers contend that the maturity of ICT is a pertinent factor in the effectiveness of Industry 4.0 initiatives (Ghobakhloo and Ching, 2019), there is the necessity to understand more in depth how ICT can affect the implementation of Industry 4.0 technologies taking into consideration the three directions for implementation above.

2.2 Digital technologies transforming businesses: from ICT to Industry 4.0

Information technology has been contributing in supporting a more concrete and effective performance measurement (Hyvönen, 2007): widespread data sources and enhanced information elaboration have been able to provide a larger set of performance measures at the firm level. During the past few decades, the diffusion of ICT allowed firms to innovate and improve business processes due to the variety of benefits linked to the evolution of these technologies (Stoel and Muhanna, 2009). According to the literature (e.g. Bayo-Moriones *et al.*, 2013; Neirotti and Raguseo, 2017), ICT solutions have been applied to three different domains within the firm and in relation to its business processes: operations and production systems, internal information processing and markets and customer management (Nieto and Fernández, 2006).

The first relevant change occurred in the application of ICT such as computer-aided design (CAD), computer-aided manufacturing (CAM) and computer numerically controlled (CNC) in production systems to support manufacturing activities (Lucchetti and Sterlacchini, 2004). The diffusion of this type of technologies allowed manufacturing firms to improve the process and coordination of manufacturing activities getting different business benefits (Xu and He, 2004).

The second technological revolution related to ICT refers to the diffusion of enterprise systems (enterprise resource planning, ERP) that support information management and specific business functions (administration, finance, production, marketing, etc.) within an integrated framework (Raymond and Uwizeyemungu, 2007). This was a revolution not only in the way information is processed within the firm (Davenport, 1998) but also mainly in how the firm is managed (Nevo and Wade, 2010). Other relevant ICT adopted by firms to manage extended business processes include technologies for production and/or supply planning, such as material requirement planning (MRP) and supply chain management (SCM), or to manage relationships with customers, such as customer relationship management (CRM) (Hendricks *et al.*, 2007; Ramdani *et al.*, 2013). The adoption of this type of ICT enabled manufacturing firms to improve their management of data with positive effects on decision-making processes (Stefanou, 2001) overcoming the firm's boundaries within the value chain.

The third fundamental change is due to the diffusion of the Internet and the web (Kelly, 1998; Porter, 2001) that promised to transform the rules of competition and especially relationships with markets, among firms (business-to-business, B2B) as well as between firms and consumers (business-to-consumer, B2C). Through web-based innovations, such as the advent of e-commerce and, more recently, social media, firms and especially small- and medium-sized enterprises (SMEs) have improved interactions with customers establishing a one-to-one relationship with positive effects on development and customization processes (Hajli, 2014).

The different groups of ICT and Industry 4.0 technologies seem to have some similarities in terms of the impact on business processes, even if they work differently (Peraković *et al.*, 2020). Industry 4.0 promises to move business transformation to a new level. In particular, the novelty of this revolution is the integration of ICT within the production system. However, different studies assessed the relationship between ICT and Industry 4.0 technologies showing that previous ICT investments have an enabling effect on adoption of Industry 4.0

(Ghobakhloo, 2018; Ghobakhloo and Fathi, 2020). Researchers found that the previous firm's ICT investment is a fundamental factor for the implementation of Industry 4.0 (Holmström *et al.*, 2016; Zangiacomi *et al.*, 2017) because of the increasing importance for organizations to align their IT strategy with their business goals (Henriques *et al.*, 2020).

Although we know that at an aggregate level ICT positively affects the implementation of Industry 4.0, knowledge about how specific groups of ICT investments affect specific groups of Industry 4.0 technologies is limited. In the scenario of performance measurement and management, it becomes important to outline how previous technological investments shape future adoptions to better outline the implications in terms of data sources and integrations as well as to evaluate how firm may exploit the technological advancement for its competitiveness through improved performance (Nudurupati *et al.*, 2016; Sahlin and Angelis, 2019). From this perspective, how the firm's ICT is linked to Industry 4.0 technologies in terms of specific groups of technologies should be explored further. In particular, we assume that the adoption of Industry 4.0 technologies follows the previous ICT experience and that the groups of ICT could affect the adoption of groups of Industry 4.0 technologies, also taking into consideration the similarities in the potentialities of the different groups in terms of efficiency, data management or customization. Therefore, our first research question is the following:

RQ1. How do different groups of ICT affect the adoption of different groups of Industry 4.0 technologies?

2.3 The role of knowledge in the digital age as a measure of performance

The wide diffusion and application of the different information technologies characterizing the digital age is strictly related to the new knowledge that such technologies allow to create and that could be useful for firms' competitiveness and performance (Ardolino *et al.*, 2018; Sahlin and Angelis, 2019). Information systems, such as CRM, ERP, SCM and MRP, are widely employed to support business and production management (Hendricks *et al.*, 2007). Computer systems, such as CAD, CAM and CNC, are widely used to support manufacturing activities and favor the development, creation and optimization of new products (Campos and Miguez, 2011). Web-based technologies, such as websites, e-commerce and social media, are used broadly to relate to the external environment and, specifically, to customers (Lee and Koubek, 2010). The use of these groups of ICT, through the generation and management of data (Dawson, 2000), can enable the creation of new knowledge (Lopez-Nicolas and Soto-Acosta, 2010), ranging from new knowledge to improve product and production quality (Yassine *et al.*, 2004) to new knowledge to develop new products or services (Leiponen, 2006). In this scenario, ICTs enhance the firm's performance measurement (Bourne *et al.*, 2018) by defining and sharing internally and within the value chain new (knowledge) process-related and product-related indicators that help the firm to better capture the performance of activities previously more difficult to obtain (i.e. in relation to communication or co-creation activities).

With respect to the previous technological waves, Industry 4.0 is, in fact, characterized by the greater possibility to gather and manage data in different business areas (Brynjolfsson and McAfee, 2014). Autonomous and advanced robotics used in the production domain can improve, through the new knowledge created by data, production (productivity and efficiency) and product (quality) performance and, at same time, have a positive impact on employees' learning process for developing new skills and competences (Kim, 2018). Three-dimensional printing allows companies to improve the design, prototyping and production of complex products, as well as product customization with customer engagement, and thus sharing of ideas to create new knowledge (Berman, 2012; Fettermann *et al.*, 2018). Finally, big data, cloud and IoT support companies in managing massive volumes of data and transforming them into valuable knowledge useful (Pauleen *et al.*, 2017) for developing new products and services (Wamba *et al.*, 2015; Weller *et al.*, 2015).

The development of new knowledge is a measure of the successful technological transformation, which managers should consider, in addition to the financial performance, to manage the different critical areas of business (Kaplan and Norton, 2001). The knowledge created using technologies is crucial for improvement in business and decision-making processes and represents a kind of nonfinancial organizational performance (Cimini *et al.*, 2020; Frederico *et al.*, 2019) that varies with respect to the different knowledge-related activities (Caputo *et al.*, 2019). In manufacturing industries, the creation of new knowledge is particularly relevant for improvement in production activities and workers' capabilities, as well as the development of new products and services, considered a knowledge-related performance of the use of technologies (Wang *et al.*, 2007).

Despite the growing literature focusing on the relevance of Industry 4.0 implementations and their connection to the creation of new knowledge and its management (Bettiol *et al.*, 2020b), further understanding of the relationship between the variety of Industry 4.0 technologies and knowledge-related performances is required, as well as for different ICT. Literature on performance measurement and management has highlighted the crucial relevance of managing intangible assets (Kaplan and Norton, 2004; Sardi *et al.*, 2019) to strengthen firm's competitive and value creation. Nevertheless, the speed and complex technological advancement open issues on how the different waves of technologies adopted impact on the organizational capability to capture the complexity of the business performances, approached in terms of (new knowledge for) the manufacturing system and market management. Therefore, the second research question is the following:

RQ2. Within the performance measurement and management framework of the firm, how do the different groups of ICT and Industry 4.0 technologies affect the firm's knowledge-related performances?

3. Methodology

In this study, we carried out a survey by administering a questionnaire through CAWI [1] methodology to entrepreneurs, chief operations officers and manufacturing managers in charge of the operational and technological processes of Italian manufacturing firms of Made in Italy sectors (broadly including automotive, furniture and home products, fashion) located in northern Italy. The focus on Italy is justified for two reasons. First, since 2016 the Italian government has promoted a "National Plan for Industry 4.0" that provides financial and fiscal support to spread the adoption of Industry 4.0 technologies among manufacturing firms. Second, firms located in northern Italy have a major relevance on Italy's gross domestic product (GDP) and on the nation's competitiveness in international markets and are thus suitable to be compared with other European Western countries (Lamorgese and Olivieri, 2017). Indeed, our research setting is interesting for two main reasons. Firstly, Italy has the highest percentage of SMEs struggling to implement Industry 4.0 principles compared to large firms. Secondly, as an important manufacturing country at the European and international levels, it is relevant for investigating firms' digitization strategies from the perspectives of Western developed economies (Zheng *et al.*, 2019).

After we contacted all 8,022 manufacturing firms in the national AIDA [2] database, we collected a representative sample of 1,400 firms whose only 206 respondents declared to have adopted at least one of the seven Industry 4.0 technologies investigated. Table 1 shows the sample characteristics, including the firm's size (EU turnover classes), industry, type of market and percentage in terms of intensity (number of technologies, from one technology to four/more technologies) of ICT and Industry 4.0 investment. The technological composition data show that, on average, firms have higher rates of ICT intensity than Industry 4.0, but also that the sample firms have different technological investments, and thus a different

Firm' size (EU revenue class)	Frequencies (%)
Micro firms (<2mln)	28.2
Small firms (2mln<€<10mln)	43.7
Medium firms (10mln<€<50mln)	22.3
Large firms (>50mln)	5.8
Industry	
Textile and clothing	22.3
Automotive	16.0
Furniture	15.6
Fashion	14.6
Electrical motors and parts	9.7
Lighting	8.7
Leather/Footwear	7.8
Rubber and plastic goods	5.3
Industry technology level	
Low/Medium-low (L/Ml)	65.5
Medium-high/High (Mh/H)	34.5
Type of market	
B2B	60.7
B2C	39.3
Number of ICT and Industry 4.0 adopted/used	
One Industry 4.0 technology	38.3
Two Industry 4.0 technologies	32.0
Three Industry 4.0 technologies	13.6
Four-to-seven Industry 4.0 technologies	16.1
One ICT	28.2
Two ICTs	14.1
Three ICTs	17.6
Four-to-nine ICTs	40.1

Note(s): $N = 206$

Table 1.
Descriptive statistics of the sample

technological profile. Because this research was an explorative cross-industry study, this is not an issue and allows us to have increased understanding of the questions investigated.

3.1 Variables

Based on literature about the implementation of Industry 4.0 in the Italian production context (Bonfanti *et al.*, 2018; Zheng *et al.*, 2019), the questionnaire aimed to assess (through a binary variable Yes = 1; No = 0) the adoption of Industry 4.0. Specifically, we asked respondents to indicate all the Industry 4.0 technologies adopted in the firm, choosing from a list of seven specific Industry 4.0 technologies: (1) autonomous robots, (2) additive manufacturing (AM), (3) big data/cloud, (4) augmented reality (AR), (5) IoT and smart products, (6) laser cutting and (7) 3D scanner. The first five technologies refer to the most mentioned ones investigated in the Italian context (Zheng *et al.*, 2019). In addition, we considered also the adoption of digital laser cutting and 3D scanner for two main reasons. Firstly, such intelligent machine tools are included in the Industry 4.0 paradigm because of their relevance for smart manufacturing (Tong *et al.*, 2020) and operational excellence (Miandar *et al.*, 2020), supporting the evolution in the customization processes of specific industries (i.e. automotive). Secondly, they are very important for the digital transformation of the Made in Italy sectors investigated (Bonfanti *et al.*, 2018) that frequently require specific technologies for the production of "tailoring goods" (Di Roma, 2017).

In addition to the Industry 4.0 technologies, we assessed some ICT most commonly used in the manufacturing context for operative and strategic goals and in relation to the different above-mentioned areas of applications: (1) production systems, (2) internal information processing, (3) market and customer management (Bloom *et al.*, 2014; Lucchetti and Sterlacchini, 2004; Ramdani *et al.*, 2013). We asked the respondents to select all the ICT used (through a binary variable Yes = 1; No = 0) among the following technologies: (1) website, (2) social media, (3) e-commerce, (4) CRM, (5) SCM, (6) ERP, (7) MRP, (8) CAD/CAM and (9) CNC.

Moreover, the questionnaire measured (with a 5-point Likert scale; 1 = not at all; 5 = very much) four knowledge-related performances linked to the use of Industry 4.0 technologies: (1) production-related knowledge (Know_prod), (2) job-related knowledge (Job_learning), (3) product-related services (Prod_service) and (4) customer-related knowledge (Co_creation), each one assessed through two items. The first two items (Know_prod) concerned the assessment of the new knowledge created to improve production and product (Dalenogare *et al.*, 2018). The second two items (Job_learning) assessed, respectively, the improvement in training for the development of new skills and then the improvement in collaboration among employees (Jain and Ajmera, 2020; Müller *et al.*, 2018). Then we assessed (Prod_service) the improvement in product performance through product-related services and the increased control over the product during use (Porter and Heppelmann, 2014). The last couple of items (Co_creation) assessed, respectively, the customer involvement in the design and then in the manufacturing processes (Mihardjo *et al.*, 2019). For each of the four knowledge-related performances, we calculated a variable as the interaction of the two items.

Finally, the questionnaire assessed firm characteristics used in the analyses as control variables. The variables referred to firm size (log of turnover and of number of employees), industry (splitting the sample between low/medium-low tech and medium-high/high tech industries following the NACE criteria), R&D expenditure, export and market type (B2B or B2C).

3.2 Data analysis

As the first step of the analysis, we performed a principal component analysis (PCA) to collapse ICT and Industry 4.0 technologies into main categories (Hair *et al.*, 2009). We followed previous studies on Industry 4.0 (Dalenogare *et al.*, 2018). The PCA helped us examine the potential contribution of the technologies, reducing them to the main categories suitable to being considered jointly for research purposes and comparing our findings with existing literature. For both types of technologies (Industry 4.0 and ICT), we used a tetrachoric correlation suitable for binary variables and small samples and avoided downward bias of the p-value estimation (Ghauri and Gronhaug, 2005). Then, we performed a regression analysis to explore the effects of ICT on Industry 4.0 technologies and a hierarchical regression analysis to assess ICT, Industry 4.0 (Model 1) and their interaction (Model 2) on knowledge-related performances.

4. Results

4.1 PCA and descriptive statistics

As shown in Tables 2 and 3, three main group of technologies were extracted from the PCA for ICT and Industry 4.0 technologies. For ICT, the PCA highlighted three different groups of technologies, with an acceptable percentage of total variance explained (73%). In particular, as shown in Table 2, SCM and MRP were excluded because of the similarity of the factor loadings (De Winter and Dodou, 2016) within the three factors extracted (SCM, factor loading 1 = 0.354, factor loading 2 = 0.568, factor loading 3 = 0.393; MRP, factor loading 1 = 0.307, factor loading 2 = 0.539, factor loading 3 = 0.331). Similarity issue reduces the percentage of

Table 2.
Rotated factor loadings ICT

ICT	Group 1 (web-based ICT)	Group 2 (management ICT)	Group 3 (manufacturing ICT)
Website	0.777	–	–
Social media	0.636	–	–
E-commerce	0.840	–	–
CRM	–	0.691	–
ERP	–	0.935	–
SCM	*0.354*	*0.568*	*0.393*
MRP	*0.307*	*0.539*	*0.331*
CAD/CAM	–	–	0.853
CNC	–	–	0.948

Note(s): N = 206; loadings lower than absolute 0.300 omitted; KMO = 0.702; Bartlett's test 267.7 (df = 36, p = 0.000); total variance explained = 73%

cumulative variance explained. We named the first group that emerged from the analysis of *Web-based ICT*; this group included websites, social media and e-commerce. The second group included ICT (ERP and CRM) used to manage internal business processes and external relationships with customers. We named this group *Management ICT*. The third group included CAD/CAM and CNC. These types of ICT support manufacturing and production processes, from design to planning and optimization. We named this group *Manufacturing ICT*, for their support role for manufacturing processes.

Regarding Industry 4.0 technologies, Table 3 highlights the three groups of Industry 4.0 technologies that emerged from the PCA, with an acceptable percentage of total variance explained (63%). Laser cutting, as SCM and MRP, was excluded because of the similarity of the factor loadings (De Winter and Dodou, 2016) within the three factors extracted (factor loading 1 = 0.358, factor loading 2 = 0.318, factor loading 3 = 0.451). The first group included autonomous robots and AR, principally used in the operations domain, to produce and/or assist and other production-related activities. Thus, we named this group *Operation 4.0*. The second group included the Industry 4.0 technologies typically used to improve product customization, such as AM and 3D scanner. We named this group *Customization 4.0*. Finally, the third factor comprised big data, cloud and IoT, technologies that allow firms to manage data. Thus, we named this group *Data-processing 4.0*. For ICT and Industry 4.0 technologies, this analysis confirmed that previous studies suggesting the variety of technological solutions that firms can use should be approached differently, taking into account the peculiarities and business opportunities that different clusters of technologies may produce.

Table 3.
Rotated factor loadings Industry 4.0 technologies

Industry 4.0 technologies	Group 1 (Operation 4.0)	Group 2 (Customization 4.0)	Group 3 (Data-processing 4.0)
Augmented reality	0.932	–	–
Autonomous robots	0.623	–	–
Additive manufacturing	–	0.914	–
3D Scanner	–	0.846	–
Laser cutting	*0.358*	*0.318*	*0.451*
Internet of things	–	–	0.759
Big data/cloud	–	–	0.710

Note(s): N = 206; loadings lower than absolute 0.300 omitted; KMO = 0.637; Bartlett's test 158.7 (df = 21, p = 0.000); Total variance explained = 63%

To evaluate the adequacy of the data for PCA, we used the Kaiser-Meyer-Olkin (KMO) test for the measure of sampling adequacy and Bartlett's test of sphericity. The tests' results suggested that the dependent variables could be reduced using PCA, because the KMO test was higher than the threshold of 0.5, and Bartlett's test of sphericity had a *p* value lower than 0.001 (Hair *et al.*, 2009).

Table 4 shows the descriptive statistics (mean scores and standard deviations) and the correlations of the variables included in the regression analyses. As expected, there is a strong positive correlation between the four knowledge-related performances, as well as between the intensity of technologies and some groups of technologies. Particularly important are the former that highlight the complementarity of technologies and performance. The other correlation values were lower than the threshold of 0.5, which is not risky (Hinkle *et al.*, 2003), and thus no multicollinearity risk arose from this.

4.2 Regression results

To explore the relationship between the firm's ICT investment and Industry 4.0 technologies implemented by manufacturing firms, we performed a regression analysis between the intensity of ICT investment (sum of ICT as an independent variable) and of Industry 4.0 (sum of Industry 4.0 technologies adopted as a dependent variable). Results reported in Table 5 show that a firm's ICT investment has a positive relationship ($B = 0.416$ $p < 0.001$) with the intensity of the Industry 4.0 technologies adopted, and that this relation does not depend on firm characteristics. The higher the number of ICT firms have, likely the higher the number of Industry 4.0 technologies the firms adopt. This observation was confirmed with the variance inflation factor (VIF) that was less than 5, which is below the acceptable threshold.

In the second step, we performed a regression analysis between the three groups of ICT and the three groups of Industry 4.0 technologies that emerged from the PCA. We regressed the three ICT groups (Web, Management and Manufacturing ICT) on each of the three Industry 4.0 technology groups (Operation 4.0, Customization 4.0 and Data-processing 4.0) performing a logistic regression analysis. For each group of technologies (ICT and Industry 4.0), we created a binary variable that considered the presence of at least one of the technologies related to the group, following previous research on innovation technology (Leiponen, 2006). In this way, we could evaluate the path dependence between the different groups of technologies (ICT and Industry 4.0). The results, shown in Table 6, are interesting. First, the Operation 4.0 group (autonomous robots and AR) is not directly linked to any of the three ICT groups, but it is related to the firm's market strategy. Results show that such technologies are mainly adopted by B2B companies ($B = -0.674$, $p < 0.05$) and thus are business-specific.

The Customization 4.0 group (AM and 3D scanner) is positively linked ($B = 0.837$, $p < 0.01$) to the Manufacturing ICT group (CAD/CAM and CNC), showing that companies focused on customization processes (i.e., CAD/CAM) invest in new technologies such as 3D printing. Results also show that the Customization 4.0 group is related to B2C companies ($B = 0.715$, $p < 0.05$), and thus to the consumer markets.

Finally, Table 6 shows that Data-processing 4.0 technologies (big data/cloud and IoT) are strongly linked ($B = 1.326$, $p < 0.001$) to Management ICT (ERP and CRM) and that firm characteristics do have not any influences. Therefore, manufacturing firms that in the past have invested in ICT to manage information and data adopted Industry 4.0 technologies to gather and management data.

In the third step of the regression analysis, we explored the relationships between Industry 4.0, ICT and the four types of knowledge-related performances, including the interactions effects of the technologies. A *p*-value of less than 0.05 was considered statistically significant. We standardized and centered independent and moderator variables before the

Table 4.
Descriptive statistics

Variables	Mean	SD	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1. Web-based ICT	0.956	0.204	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
2. Management ICT	0.228	0.421	−0.054	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
3. Manufacturing ICT	0.578	0.495	0.010	0.278***	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
4. Intensity ICT	3.049	1.910	0.192**	0.569***	0.687***	–	–	–	–	–	–	–	–	–	–	–	–	–	–
5. Operation 4.0	0.510	0.501	0.075	−0.022	0.105	0.137*	–	–	–	–	–	–	–	–	–	–	–	–	–
6. Customization 4.0	0.403	0.492	0.079	0.143*	0.101	0.156*	−0.085	–	–	–	–	–	–	–	–	–	–	–	–
7. Data-processing 4.0	0.510	0.501	0.028	0.256***	0.026	0.224**	−0.146*	0.053	–	–	–	–	–	–	–	–	–	–	–
8. Intensity I4.0	2.180	1.329	0.047	0.301***	0.264***	0.433***	−352***	0.575***	0.382***	–	–	–	–	–	–	–	–	–	–
9. Prod_know	7.680	6.833	0.084	0.250***	0.408***	0.436***	0.229**	0.033	0.074	0.315***	–	–	–	–	–	–	–	–	–
10. Job_learning	5.165	4.895	0.007	0.292***	0.371***	0.414***	0.248***	0.067	0.067	0.312***	0.619***	–	–	–	–	–	–	–	–
11. Prod_service	5.155	5.337	0.060	0.136	0.272***	0.341***	0.094	0.104	0.237**	0.325***	0.521***	0.445***	–	–	–	–	–	–	–
12. Co-creation	4.325	4.993	0.071	0.062	0.281***	0.261***	0.257***	0.111	0.011	0.336***	0.397***	−397***	0.442***	–	–	–	–	–	–
13. Industry tech level (L/Ml – Mh/H)	0.345	0.476	0.105	−0.029	−0.124	−0.061	0.078	0.091	0.057	0.025	−0.077	−0.081	0.050	−0.162	–	–	–	–	–
14. Market (B2B-B2C)	0.393	0.490	−0.120	0.154*	−0.076	0.058	−0.185**	0.007	0.014	−0.057	−0.019	0.011	0.034	−0.112	−0.019	–	–	–	–
15. Turnover (Log)	1.472	0.517	0.032	0.125	0.110	0.253***	0.163*	0.104	0.111	0.227**	0.036	0.092	0.037	−0.035	0.126	−0.087	–	–	–
16. Employees (Log)	3.671	0.639	−0.014	0.114	0.020	0.167*	0.117	0.080	0.106	0.152*	−0.057	0.021	0.009	−0.146*	0.137*	0.008	0.837***	–	–
17. R&D	3.662	7.009	0.058	0.141*	0.167*	0.196**	0.012	0.111	0.097	0.142*	0.207**	0.215**	0.131	0.252***	0.046	−0.042	−0.080	−0.097	–
18. Export	34.52	34.56	0.045	0.293***	0.157*	0.205***	0.023	−0.093	0.098	0.044	0.151*	0.090	−0.032	0.003	0.000	0.149*	0.162*	0.139*	0.137*

Note(s): $N = 206$; ***$p < 0.001$; **$p < 0.01$; *$p < 0.005$

	B	t	Sig	VIF
Independent variable				
ICT endowment	0.416	6.060	0.000	1.203
Control variables				
Industry tech level (L/Ml – Mh/H)	0.037	0.586	0.558	1.040
Market (B2B-B2C)	−0.053	−0.823	0.412	1.074
Turnover (log)	0.181	1.518	0.131	3.643
Employees (log)	−0.055	−0.472	0.637	3.452
R&D	0.079	1.205	0.230	1.089
Export	−0.089	−1.343	0.181	1.125

Note(s): $N = 206$; $R = 0.475$; $R^2 = 0.226$; adjusted $R^2 = 0.198$; $F = 8.242$ ($p = 0.000$)

Table 5. Linear regression between the ICT and Industry 4.0 intensity

	Operation 4.0[a]	Customization 4.0[b]	Data-processing 4.0[c]
ICT groups			
Web-based ICT	0.460	0.503	0.325
Management ICT	−0.220	0.100	1.326***
Manufacturing ICT	0.415	0.837**	−0.271
Control variables			
Industry tech level (L/Ml – Mh/H)	0.294	−0.006	0.162
Market (B2B-B2C)	−0.674*	0.715*	−0.085
Turnover (log)	0.540	0.161	0.239
Employees (log)	0.010	−0.143	0.105
R&D	−0.001	0.025	0.027
Export	0.001	−0.008	0.001

Note(s): $N = 206$; ***$p < 0.001$; **$p < 0.01$; *$p < 0.05$; [a] Log Likelihood = 270.628; Cox and Snell $R^2 = 0.070$; Negelkerke $R^2 = 0.093$; $\chi^2(9) = 14.870$ ($p < 0.05$); [b] log likelihood = 258.143; Cox and Snell $R^2 = 0.071$; Negelkerke $R^2 = 0.093$; $\chi^2(9) = 15.176$ ($p < 0.05$); [c] log likelihood = 267.318; Cox and Snell $R^2 = 0.084$; Negelkerke $R^2 = 0.113$; $\chi^2(9) = 7.089$ ($p < 0.05$)

Table 6. Logistic regressions among ICT and Industry 4.0 groups

analysis (Aiken and West, 1991). As shown in Table 7, the main results refer to the direct relationships between some groups of Industry 4.0 technologies, ICT and the four knowledge-related performances assessed (Model 1). The Operation 4.0 group (autonomous robots and AR) affected three knowledge-related performances: Know_prod ($B = 0.224$, $p < 0.001$), Job_learning ($B = 0.244$, $p < 0.001$) and Co_creation ($B = 0.274$, $p < 0.001$). The other two groups of Industry 4.0 technologies were positively linked with only one type of knowledge-related performance: Customization 4.0 with Co_creation ($B = 0.142$, $p < 0.05$) and Data-processing 4.0 with Prod_service ($B = 0.263$, $p < 0.001$).

In addition to Industry 4.0 groups, we considered the three ICT groups, and they also were positively linked to knowledge-related performances. Specifically, Manufacturing ICT was linked with Operation 4.0, with all knowledge-related performances (Know_prod: $B = 0.300$, $p < 0.001$; Job_learning: $B = 0.255$, $p < 0.001$; Prod_service: $B = 0.255$, $p < 0.001$; Co_creation: $B = 0.164$, $p < 0.05$). Management ICT was linked only with Job_learning ($B = 0.193$, $p < 0.01$). Finally, the Web-based ICT group was not linked directly with any of the knowledge-related performances.

Regarding the interaction effects, Table 7 shows (Model 2) few marginally significant relationships between Manufacturing ICT with Operation 4.0 and Job_learning ($B = 0.140$, $p < 0.05$) and Co_creation ($B = 0.198$, $p < 0.01$), and between Web-based ICT with

Table 7.
Hierarchical regression with interaction effects on knowledge-related outcomes

Independent variables	Know_prod[a] Model 1	Know_prod[a] Model 2	Job_learning[b] Model 1	Job_learning[b] Model 2	Prod_service[c] Model 1	Prod_service[c] Model 2	Co_creation[d] Model 1	Co_creation[d] Model 2
Operation 4.0	0.215***	0.203**	0.242***	0.225***	0.121	0.104	0.266***	0.249***
Customization 4.0	−0.009	−0.032	0.014	−0.009	0.046	0.013	0.138*	0.074
Data-processing 4.0	0.057	0.036	0.037	0.000	0.243***	0.220**	0.049	0.029
Web-based ICT	0.067	0.101	−0.001	0.016	0.046	0.083	0.035	0.083
Management ICT	0.131	0.144	0.192**	0.145**	0.014	−0.016	−0.017	−0.072
Manufacturing ICT	0.311***	0.321***	0.258***	0.274***	0.266***	0.281***	0.182**	0.207**
Interaction effects								
Web-based * Operation4.0		0.067		−0.063		0.063		0.063
Web-based * Custom 4.0		−0.022		0.102		−0.001		0.064
Web-based * Data 4.0		0.051		0.107		0.167*		0.109
Management * Operation 4.0		0.130		0.022		0.106		0.009
Management * Custom 4.0		0.017		0.137		0.119		−0.005
Management * Data 4.0		−0.013		−0.017		0.023		0.092
Manufacturing * Operation 4.0		0.102		0.140*		0.108		0.198**
Manufacturing * Custom 4.0		0.055		0.035		0.021		0.074
Manufacturing * Data 4.0		−0.022		−0.021		−0.034		0.008
Control variables								
Industry tech level (L/Ml – Mh/H)	−0.053	−0.045	−0.071	−0.055	0.053	0.059	−0.169*	−0.146*
Market (B2B-B2C)	0.042	0.031	0.070	0.055	0.100	0.100	−0.017	−0.044
Employees (log)	0.118	0.070	0.126	0.051	0.007	−0.054	0.163	0.132
Turnover (log)	−0.193	−0.158	−0.115	−0.056	−0.032	0.008	−0.281*	−0.254*
R&D	0.115	0.118	0.149*	0.144*	0.068	0.078	0.200**	0.205**
Export	0.035	0.039	−0.050	−0.022	−0.124	−0.114	−0.036	−0.010

Note(s): $N = 206$; ***$p < 0.001$; **$p < 0.01$; *$p < 0.05$; [a] Model 1: $R = 0.516$; $R^2 = 0.266$; adjusted $R^2 = 0.220$; $F = 5.823$ ($p = 0.000$), Model 2: $R = 0.554$; $R^2 = 0.307$; adjusted $R^2 = 0.228$; $F = 3.885$ ($p = 0.000$), R^2 change = 0.041 ($p = 0.284$); [b] Model 1: $R = 0.509$; $R^2 = 0.259$; adjusted $R^2 = 0.213$; $F = 5.615$ ($p = 0.000$), Model 2: $R = 0.557$; $R^2 = 0.310$; adjusted $R^2 = 0.232$; $F = 3.945$ ($p = 0.000$), R^2 change = 0.052 ($p = 0.138$); [c] Model 1: $R = 0.412$; $R^2 = 0.170$; adjusted $R^2 = 0.118$; $F = 3.296$ ($p = 0.000$), Model 2: $R = 0.488$; $R^2 = 0.238$; adjusted $R^2 = 0.151$; $F = 2.739$ ($p = 0.000$), R^2 change = 0.066 ($p = 0.068$); [d] Model 1: $R = 0.499$; $R^2 = 0.249$; adjusted $R^2 = 0.202$; $F = 5.321$ ($p = 0.000$), Model 2: $R = 0.557$; $R^2 = 0.310$; adjusted $R^2 = 0.232$; $F = 3.943$ ($p = 0.000$), R^2 change = 0.062 ($p = 0.065$)

Data-processing 4.0 and Prod_service ($B = 0.167, p < 0.05$). However, the R^2 change between Model 1 and Model 2 of the three knowledge-related performances affected by integration variables was not statistically significant; thus, Model 1 with only direct effects of independent variables was preferred.

5. Discussion

The preliminary goal of this analysis was to determine whether ICT and Industry 4.0 technologies could be grouped into main categories. PCA showed that both types of technologies can be grouped into three main clusters. For ICT, previous investment by manufacturing firms focused on specific groups of ICT for achieving specific strategic benefits in terms of production, internal information management and interactions with the external environment (Barba-Sánchez *et al.*, 2007).

For Industry 4.0, the data allowed us to verify suggestions about the three main directions that could affect the adoption of new technologies emphasizing a cluster of technologies for operation processes, a cluster that encompasses technologies for customization, and a cluster of technologies for data processing. In this way, we can position the findings in the middle of the debate about Industry 4.0 clusters, with slight similarities and differences (Culot *et al.*, 2020a; Frank *et al.*, 2019a; Oztemel and Gursev, 2020) that depend on the peculiarities of the industries investigated (Culot *et al.*, 2020b; Ghobakhloo and Ching, 2019).

Referring to the relationships between ICT and Industry 4.0, the results of the first step of the regression analyses showed a significantly strong relationship between ICT investment and Industry 4.0 intensity, highlighting that the more a firm invested in ICT in the past, the higher the probability the firm would invest in several Industry 4.0 technologies today. From this perspective, ICT investment is the technological base upon which manufacturing firms implement Industry 4.0, and this link is not influenced by firm characteristics, such as size and industry. Previous ICT investment stresses the strategic readiness of manufacturing firms in implementing Industry 4.0 (Ghobakhloo and Fathi, 2020). From the performance measurement and management perspective, our result confirms the relevance of interdependence and relationship between different waves of technological investments (as key assets of the firm).

The second step of the regression analysis explored how specific groups of ICT affect the adoption of specific groups of Industry 4.0 technologies, stressing the relevance of the IT alignment strategy with previous technological investment also in terms of groups of technologies (Kane *et al.*, 2015a). There are two main findings concerning these links. First, there is a direct relationship between previous investments in manufacturing ICT and customization Industry 4.0. Manufacturing firms that focused their ICT investment on supporting manufacturing activities, such as CAD/CAM, showed higher probability of implementing Industry 4.0 technologies for flexibility and customization purposes, such as 3D printing and scanner. These results suggest that manufacturing firms could combine ICT such as CAD/CAM with the additive manufacturing and 3D scanner for optimizing product customization, to create an effective production system for mass personalization (Wang *et al.*, 2017). However, no relationship emerged between Manufacturing ICT and Operation 4.0, suggesting a more independent path of adoption concerning the smart factory domain focused on efficiency and productivity, which, instead, depends on the type of market served (B2B).

Second, manufacturing firms with ICT investments centered on technologies for managing information and business processes (ERP, CRM) digitally likely will focus on data processing technologies (cloud, big data and IoT) in implementing Industry 4.0. According to the results, firms combine the technological infrastructure previously built for managing information within the firm with the new opportunities offered by Industry 4.0, such as new analytical tools (big data) and hardware devices (sensors). The information management started with the first wave of ICT (such as ERP) is improved, thanks to the implementation of new data technologies (such as cloud and big data), suggesting the development of firm capabilities enabling such technological advancement (Gupta *et al.*, 2018). This result concerning the powerful role of technologies to map and support data management for strategic reasons can be seen as an enhancement of the firm's potential in measuring and managing performances putting together different data sources but also different technological tools. On the contrary, compared to the two other groups of ICT, Web-based ICT does not seem to have any influence in the implementation of Industry 4.0. In this case, the absence of a direct relationship could be related to technological immaturity or to the fact the firms focused their investments mainly on the production floor.

Regarding the second research question, this study showed how Industry 4.0 technologies and ICT affect knowledge-related performances. Among the set of technologies investigated, the groups Operation 4.0 and Manufacturing ICT are those that mostly affect the knowledge-related performances. This result seems to suggest that digitalization in relation to the firm's manufacturing internal processes can improve the development and management of knowledge on multiple levels, where the different technologies involved enhance the creation and monitoring of new knowledge within the operation department and processes. In particular, regarding Industry 4.0, the Operation 4.0 group affects the knowledge-related performances in the production domain (improvement of production process, job-related learning and co-creation). In this area, we expect automating production processes will require a certain capability of employees to automatically, autonomously add value in new products and new production solutions (Kane *et al.*, 2015b). In this regard, Manufacturing ICT are also important technologies for knowledge, with a slight interaction effect of both technologies on the co-creation process.

In terms of the other groups of Industry 4.0 technologies, the Data-processing 4.0 group affects product-related services (i.e. after-sale services). This result is consistent and enriches previous research, suggesting that these technologies may enhance servitization, thus helping the firm in enhancing knowledge management with respect to the market and customers (Valtakoski, 2017). In this scenario, the implementation of new, more advanced technologies further sustains the identification of new business areas and processes where investing to enhance the firm's competitive advantage (Nudurupati *et al.*, 2016). However, the Customization 4.0 group is important in terms of co-creation jointly with the Operation 4.0 group, as co-creation involves design and production activities. This finding enriches studies on co-creation as a knowledge-intensive process where digitalization of production processes (Ramaswamy and Ozcan, 2018) that enact product customization further supports the development of new knowledge rooted in customer–firm interaction and translated into a new offering through advanced Industry 4.0 solutions. The opportunity to exploit knowledge related to customers' inputs mainly characterizes innovative (R&D) small medium-low tech firms. Moreover, the simultaneous use of Operation 4.0 and Manufacturing ICT could replace the direct effect of Customization 4.0 technologies.

In addition to Industry 4.0 technologies, ICTs have a positive relationship with knowledge-related performance. Management ICT are important for the learning process in the work environment, where the possibility to advance information management and transfer as well as process codification further develops knowledge at the employee level. Counterintuitively, Web-based ICTs are not directly related to any of the knowledge-related performances. This evidence may be explained by the fact that firms may use these technologies with limited attention to the possibility of acquiring knowledge from customers and leverage on such knowledge by measuring and monitoring it (Kaplan and Norton, 2001).

6. Conclusions

The study is one of the first to explore the relationship between groups of ICT and Industry 4.0 technologies, and between such technologies and knowledge-related performance. In the current debate on the evolution of performance measurement and management systems within the Industry 4.0 digital environment (Frederico *et al.*, 2019), our study provides additional evidence on how different interconnected technologies may sustain the advancement of business processes through the new knowledge that becomes an output indicator of technology innovation and thus a measure of successful technology use. Based on original data and extensive empirical analysis, this research showed a strong path dependency between the use of ICT and Industry 4.0, namely, taking into account different groups of technologies. By using ICT, firms learn the logic and rules of digitalization of business processes and activities, which will be further applied within the Industry 4.0 context. In this view, the cumulative effect is due to a learning process that enriches digital capabilities (Khalil and Belitski, 2020) and resources (Ghobakhloo and Fathi, 2020) to take advantage of new possibilities offered by digital technologies. The more trained a firm is in the use of digital technologies, the more ready the firm will be to take advantage of the new possibility of the next wave of digital technologies. Such findings advance literature on the implementation paths of Industry 4.0, as well as on the necessity for technology maturity and expertise to cope with major technological revolutions in the industry (Tang and Ghobakhloo, 2013).

The need for a comprehensive technology strategy is more evident if we consider the relationships among the components of ICT and Industry 4.0 groups of technologies. We observed a specific combination of technologies that has a strategic component that allows us to assert that there is strong coherence in the combination of old (ICT) and new (Industry 4.0) technologies. In general, we observed several bonds between Industry 4.0 and the first waves of ICT implementation. The benefits of Industry 4.0 have strong roots in ICT. We could identify a cumulative effect in the way firms may capture knowledge and leverage on past learning to strengthen the positive consequences of the technological adoption on strategies (Smith and Bititci, 2017).

In addition to the effects on implementation paths, the links between ICT and Industry 4.0 are relevant from the perspective of knowledge creation. The opportunity to use Industry 4.0 technologies for different purposes (improvement of product and production, of marketing and co-creation processes, of learning processes) enhances the creation of new knowledge that firms, especially in the manufacturing context, should use to sustain competitiveness. Knowledge-related performance becomes an essential performance measure of technology use complementary to other performance indicators, especially within the Industry 4.0 paradigm (Robert *et al.*, 2020). In this regard, the study contributes to advancing literature about the relationships between technologies and knowledge-related performance. Industry 4.0 and ICTs used in the production domain, such as autonomous robots, augmented reality, CAD/CAM and CNC, seem to play a key role in affecting different knowledge-related performance. In this regard, manufacturing firms focused on operations achieve knowledge-related performances in terms of productivity, efficiency and flexibility with data and then of knowledge that they are able to create and use (McAfee and Brynjolfsson, 2012), as well as improve the job-related learning process. Data-processing technologies instead confirm their key role for the servitization process (Frank *et al.*, 2020b), and additive manufacturing confirms its strategic role for customer involvement. The role that knowledge has in sustaining competitiveness depends on decision-making that can be effectively supported by a knowledge-based information system (Taticchi *et al.*, 2015). In this sense, the study allows us to advance literature on the consideration of knowledge creation as a non-financial form of Industry 4.0 performance.

From a managerial point of view, the results suggest that firms trained in coping with technological and business challenges in the past are more ready to exploit the next technological wave for business opportunities. At the same time, the results highlight the path dependence among the different groups of technologies, where specific previous investments in ICT (i.e., in Management and Manufacturing ICT) then lead firms to the following adoption of related Industry 4.0 technologies. This is a positive performance of having internal ICT resources in the context of Industry 4.0. However, this finding does not exclude that firms could implement ICT and Industry 4.0 simultaneously, but that is unlikely, at least for established firms. On the contrary, it is possible that start-ups or new ventures can invest in ICT and Industry 4.0 at the same time.

A second relevant result of the research is related to the role of ICT-related competences firms have to internally develop to adopt Industry 4.0 technologies. It is not a matter of size *per se*. Rather, for firms (as well as SMEs), it becomes more important in the context of Industry 4.0 to rely on internal resources (know-how connected to the ICT domain) that can positively enact the selection and exploitation of Industry 4.0 technologies. In this perspective, as a policy implication, pushing the adoption of Industry 4.0 technologies in firms with limited ICT resources should be coupled with actions supporting the development of such know-how and broader ICT competences as the roots for Industry 4.0.

Finally, managers should consider forms of knowledge measurements to evaluate successful implementation of Industry 4.0 and respond effectively to the revolutionary changes (Yunus, 2020). To understand the success or otherwise of an organization's activities, it is essential to find key indicators that measure performance (KPIs). In this regard, organizations need to demonstrate the links between the use of technologies, the resultant knowledge and the impact on performance.

The lack of a direct evaluation of the knowledge-related performances on economic and financial performance is one of the limitations of the study that could be analyzed in future research. Knowledge-related performance linked to the use of Industry 4.0 should be operationalized in terms of efficiency and effectiveness, as a performance measurement system includes a mix of financial and non-financial data. In this regard, future research should analyze the effects of the different groups of Industry 4.0 on performance indicators, such as productivity and profitability, through the knowledge-related performances of the use of technologies.

Another research limitation refers to the sample and the technologies. The sample should be enlarged to include the international context of Europe and other Industry 4.0 technologies. Specifically, the study could consider countries with similar firm manufacturing systems (in particular as far as SMEs are concerned) as well as countries promoting Industry 4.0 policies to further expand the analysis and provide additional support of the results achieved. One more limitation is that cross-section data were used (based on 2017), and Industry 4.0 is a dynamic phenomenon that could be fully analyzed for a longer period. Future research should expand the analysis of the implications for performance management of the adoption of Industry 4.0 technologies in firms in different industries.

Notes

1. Computer-assisted web interview (CAWI) methodology was selected because it is appropriate for contacting a large sample. To interview entrepreneurs, COOs and manufacturing managers, we conducted a prescreening through information available online or through a dialogue with the firm with the aim of having, when possible, the personal email of the contact person.
2. AIDA is provided by Bureau Van Dijk, a Moody's analytics company. AIDA contains comprehensive financial and economic information on companies in Italy, with up to 10 years of historical data.

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