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Firm's openness and innovation in Industry 4.0

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Abstract

Purpose – The purpose of this paper is to investigate the role of firms' features on innovation performance in Industry 4.0, focusing on the concepts of breadth and depth of openness in the innovation process.

Design/methodology/approach – Using data gathered from 96 firms active in Industry 4.0 (I4.0) in Italy, a Poisson regression analysis is conducted to investigate the relationship between the openness of firms' innovation processes at the level of knowledge sources and their innovation performance in I4.0.

Findings – The results highlight the relationship between the level of openness and innovative performance in I4.0. In particular, the breadth of the openness of the innovation process of enterprises is curvilinearly related to innovation in I4.0, taking an inverted U-shape.

Practical implications – Managers of firms operating in I4.0 should consider openness as a strategic response to the knowledge requirements and risks associated with the innovation process in complex technologies.

Originality/value – Through the questionnaires administered mainly to highly qualified individuals, an original and unique database has been created with information on the openness of the innovative process and the innovation performances in I4.0.

Keywords Industry 4.0 (I4.0), Open innovation (OI), Openness, Breadth, Depth

Paper type Research paper

1. Introduction

The digitization of industrial-manufacturing processes and in particular Industry 4.0 (I4.0) for many authors emerges as a central process of the Fourth Industrial Revolution (4RI) (Park, 2018). The first report that introduces the 4RI is the WEF (2016), which describes the 4RI as the advent of cyber-physical systems. Park (2018) is one of the first authors to discuss 4RI, a transition techno-economy paradigm that sees the convergence of numerous and emerging technologies such as artificial intelligence, robotics, Internet of Things, autonomous vehicles, 3D printing, nanotechnology, biotechnology and cloud computing.

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Given the economic relevance of I4.0, there has been a notable surge in academic research to shed light on various aspects, challenges and solutions concerning the design, implementation and management of I4.0 (Hervás-Oliver *et al.*, 2021; Hervás-Oliver, 2021, 2022) However, limited attention has been paid to the innovation process within this domain, particularly exploring the role of collaboration and openness in Industry 4.0. This leads to the research question of this article:

RQ1. How do companies embrace the dynamics of open innovation (OI) to foster innovation in Industry 4.0?

To address this question, the present article builds upon the concept of OI, as introduced by Chesbrough (2003), which advocates for the inclusion of external sources of knowledge in the innovation process of companies. By adopting an OI model, companies gain the ability to tap into external knowledge and capitalize on new technological opportunities, thereby augmenting their innovative capacity. Research on openness has expanded subsequent to Chesbrough's seminal work. Several studies have demonstrated a nonlinear relationship between the degree of openness in the innovation process and innovative performance (Laursen and Salter, 2006; Leiponen and Helfat, 2010).

The objective of this article is to examine the importance of company characteristics in relation to innovative performance within the context of Industry 4.0, specifically focusing on external knowledge sourcing. In the literature, it is recognized that firms with greater access to knowledge sources tend to innovate more, but this relationship often exhibits an inverted U-shaped pattern (Laursen and Salter, 2006; Leiponen and Helfat, 2010; Capone and Innocenti, 2020).

This study seeks to explore how the characteristics of the knowledge-source process could impact the ability of companies to innovate effectively in I4.0. The level of knowledge sourcing in the innovative process has been investigated thanks to two concepts introduced for the first time by Laursen and Salter (2006). The first concept concerns *breadth* and is defined as the number of external sources on which companies rely for innovation. The second concept is that of *depth*, defined in terms of the intensity with which companies collaborate with various external sources.

An empirical study was conducted on a sample of 96 Italian companies situated in I4.0 clusters in Italy to investigate their innovative performance in I4.0 (measured by the number of I4.0 technologies in which a firm innovates). These companies were surveyed using a questionnaire specifically designed to investigate the role of opening the innovation process in I4.0, with approximately 90% of the replies coming from highly qualified individuals operating in the considered companies.

The findings of the study underline the correlation between the degree of openness and innovative performance. Furthermore, the results confirm an inverse U-shaped curvilinear relationship in the context of I4.0, showcasing the interplay between innovation, the opening of the innovation process and collaborations. This emphasizes the importance of collaborations in the I4.0 landscape while also shedding light on the potential risks and costs associated with such partnerships.

The remainder of the article is divided as follows: After this introduction, Section 2 delves into the existing literature surrounding openness and innovation within the context of I4.0, presenting the hypotheses of the study. Section 3 outlines the research design and the data source. Section 4 presents the empirical analysis. Section 5 concludes the article, highlighting several managerial implications.

2. Industry 4.0 and the openness of the innovation process

2.1 Industry 4.0 and the role of clusters

The term Industry 4.0 originated from the German initiative "Industrie 4.0," which was introduced in 2011 at the Hanover fair and designated as an integral component of the German High-Tech Strategy of the 2020 (Hermann, Pentek and Otto, 2016).

Industry 4.0 entails a novel industrial landscape where diverse emerging technologies converge, resulting in the establishment of physical-digital systems capable of effectively managing production complexities and generating increased value for businesses (Zhou *et al.*, 2015). Consequently, intelligent factories are emerging, characterized by interconnected machines, devices and products that adapt to real-time market changes (Hermann *et al.*, 2015). It is well understood that Industry 4.0 has the potential for a significant long-term strategic impact on global industrial development (EU, 2015).

Industry 4.0 presents a significant opportunity for companies that are increasingly recognizing the advantages it offers. According to the European Commission (2018), nearly 90% of European companies perceive these new technologies as opportunities.

There is notable heterogeneity among different economies worldwide, which determines their varying ability to embrace I4.0. Disparities between countries arise from factors such as labor market flexibility, skill levels of the workforce, the adequacy of digital infrastructure and the level of legal protection. Sang-Chul Park (2018) compiled a readiness ranking of economies for the fourth industrial revolution, with Western and Northern European countries (Finland, Sweden, Denmark and Norway) occupying the top positions. The USA and the UK also play prominent roles among Anglo-Saxon nations. However, Italy does not feature among the top 24 countries in the ranking and is placed at number 33.

Deloitte (2018) highlights Italy's solid position in Europe and globally regarding the adoption and application of technologies enabling I4.0. The country stands among the leading European states in terms of high-tech companies in both the manufacturing and services sectors. Italy also surpasses the European average in the production and utilization of industrial robots, as well as the implementation of technologies such as the IoT and machine-to-machine communication.

However, the Ministry of Economic Development reveals that in 2017, only 8.4% of companies in Italy used at least one enabling technology for I4.0. Additionally, there is heterogeneous diffusion of these technologies at the regional level, with the central-northern regions of Italy exhibiting a higher prevalence (MiSE, 2018).

Hence, it is crucial to highlight that a portion of the literature has examined the role of I4.0 in various specific contexts, including clusters and industrial districts (Hervás-Oliver *et al.*, 2021; De Propris and Bailey, 2021). Some studies explore the theoretical connection between I4.0 and clusters, while others focus on case studies of particular clusters, investigating aspects such as the adoption, implementation and effects of I4.0 in different locations [e.g. Poland-Germany (Götz and Jankowska, 2017)].

The number of works examining industrial clusters is limited, primarily concentrating on countries such as Italy and Spain (Bettiol *et al.*, 2020; Pagano *et al.*, 2020; Hervás-Oliver, 2022; Burlina and Montresor, 2021). These studies underscore the significant impact that I4.0 can potentially have in Italy (Bellandi *et al.*, 2020). Finally, several definitions of innovation are adopted in the different studies, ranging from the count of innovations in I4.0 to the intensity of innovation, etc. (Büchi *et al.*, 2020; Culot *et al.*, 2020; Bettiol *et al.*, 2023).

2.2 Openness and the effect on innovation in Industry 4.0

Previous authors have primarily focused on opening up the innovation process outside the I4.0 context (Henkel, 2009; Herzog and Leker, 2010; Chiaroni *et al.*, 2011; Enkel and Bader, 2013).

Chesbrough (2003) initially highlighted that adopting OI practices can enhance a firm's innovation productivity, as firms embracing OI tend to be more innovative than closed innovation organizations. Several studies have identified the potential benefits of opening up the innovation process. Kovacs *et al.* (2015) introduced a strand of research called "performance-oriented publications," which demonstrates the positive effect of opening up the innovation process on innovation productivity. Benassi *et al.* (2022) and Bettiol *et al.* (2023) verified an increase in labour productivity adopting technologies in I4.0, while Greco *et al.* (2015) provide empirical evidence linking OI actions and innovation performance.

Recent studies underline that innovating in I4.0 needs an open and collaborative environment because of the complexity of the new technologies and the heterogeneous capabilities needed (Reischauer, 2018). Rocha *et al.* (2019) emphasize the significance of accessing external knowledge and technology for I4.0 innovations, particularly through collaborations with startups. Reischauer (2018) highlights the importance of collaboration in innovation ecosystems that encompass universities, companies and governments in I4.0. Urbinati *et al.* (2017) emphasize the role of digital technologies in managing an OI process, specifically mentioning big data, the IoT and cloud computing. Numerous studies have demonstrated the impact of digital technologies on open and collaborative innovation approaches (Brunswicker *et al.*, 2015; Urbinati *et al.*, 2017).

Despite the growing interest in I4.0 and the importance of collaboration, few studies have examined the role of opening up the innovation process in this evolving context, while in general, it has already been studied since the early 2000s. Laursen and Salter (2006) have made a significant contribution to studying the impact of strategies for accessing external ideas on innovation. They introduce two concepts that represent the opening of innovative business processes. The first concept, the *breadth* of collaboration, refers to the number of external sources or research channels used by companies in their innovative activities. The second concept, the *depth* of collaboration, is defined in terms of the intensity with which companies draw ideas from various external sources or research channels.

The approach used by Laursen and Salter (2014) focuses on the research channels (such as customers, suppliers, competitors and universities) that companies use to identify innovative opportunities. The authors explore the innovation process using a sample of 2,707 manufacturing companies in the UK and find a positive correlation between breadth and depth of collaboration and innovative performance.

The literature on the breadth and depth of firms' external search strategies has highlighted advantages such as reducing uncertainty, accessing diverse resources and exploiting greater technological opportunities (Bernal *et al.*, 2019).

Leiponen and Helfat (2010), analysing the research strategies of external ideas in a sample of 339 manufacturing companies in Finland, find that collaboration with different sources of technologies and knowledge has a positive impact on innovations. Collaboration with a limited number of external partners can involve a form of myopia that can prevent companies from seizing technological possibilities from other channels.

Amara and Landry (2005), in their study of a sample of Canadian manufacturing companies, also found that companies that use a wider variety of knowledge sources that carry out research (e.g. universities and research centres) are more likely to introduce innovations with a high degree of novelty.

Liu (2021), focusing on the Chinese electronic information industry, has found that both the breadth and depth of external search have beneficial impacts on radical and incremental innovation performance. The study by Lorenz *et al.* (2020) on Swiss manufacturers found that a deeper external search was associated with higher adoption of most digital technologies. However, the results were not conclusive regarding the relationship between external search breadth and the adoption of digital technologies.

Lu *et al.* (2020), investigating SMEs in China, indicate again that both breadth and depth are positively related to innovation performance. The study by Lyu *et al.* (2020) demonstrates that both breadth and depth of openness promote firm innovation radicalness. Duan *et al.* (2021) looked at high-tech manufacturing companies located in China. They studied the effects of both the breadth and the depth of technology on the quality of innovation, which they determined by calculating the proportion of granted patents for inventions to the total number of patent applications. The results showed that both a broad and deep search for technology have a reverse U-shaped relationship with innovation quality.

In summary, all studies suggest that innovation carried out in a wider and more collaborative way allows for a higher level of innovative performance. Based on the above literature and applying it to the context of innovation in I4.0, the following hypotheses are therefore proposed:

H1a. The breadth of the collaborations is positively correlated with the innovative performances in Industry 4.0.

H1b. The depth of the collaborations is positively correlated with the innovative performances in Industry 4.0.

Nevertheless, the opening of the innovation process brings not only advantages but also incurs costs, both monetary and non-monetary (Laursen and Salter, 2014). These costs tend to escalate as the level of openness increases. According to Salge *et al.* (2013), increased openness necessitates financial and human resources to absorb, identify, assimilate and apply external knowledge, leading to the challenge of absorption capacity (Cohen and Levinthal, 1990).

Excessive openness can have a detrimental impact on innovative performance because of two additional reasons (Laursen and Salter, 2006). The first reason pertains to the issue of timing, wherein innovative ideas may not always align with the opportune moment for exploitation. The second reason relates to the attention allocation problem, which arises when there are a multitude of ideas. In such cases, companies may fail to allocate sufficient attention to relevant ideas, resulting in missed opportunities. These challenges imply that businesses may face higher marginal costs because of the increased complexity of managing a broader range of knowledge (Leiponen and Helfat, 2010).

Observing the costs of the depth of collaboration, some companies may become too dependent on external sources for innovation if they set up the same deep relationships. Maintaining these links requires resources and energy. The use of the same knowledge for a long period of time can also generate rigidity problems (Bernal *et al.*, 2019). Therefore, if a company has too many deep relationships with many external sources, it can show a reduction in innovative performance.

On the other hand, the benefits of opening up may decrease as the number of sources increases. Once a certain level of openness to research has been reached, external knowledge will become increasingly redundant, incompatible and irrelevant, thus offering diminishing marginal advantages (Salge *et al.*, 2013). The same problem of information redundancy arises in the case of deep ties with external partners, as these lead to the overlapping of the knowledge bases of companies (Bernal *et al.*, 2019).

It is also possible to highlight some other potential detrimental effects of both breadth and depth in external knowledge sourcing: breath overload and depth-induced stagnation

(Dong and Netten, 2017). In the first concept, overemphasis on breadth in external knowledge sourcing, while valuable for diversity, can lead to information overload and the diffusion of efforts. This deluge of information may overwhelm innovation teams, making it challenging to discern valuable insights from noise and resulting in a lack of coherent direction in the innovation process. In the second, an exclusive focus on in-depth sourcing from a limited pool of external knowledge providers can inadvertently stifle innovation. Relying too heavily on a single source or a narrow set of sources may create a myopic view of possibilities, limiting exposure to fresh ideas and alternative perspectives critical for breakthrough innovation.

Balancing the breadth and depth of external knowledge sourcing is vital to harnessing the full potential of external insights while avoiding these detrimental effects on the innovation process.

Consistent with these concepts, several studies have identified a threshold where the costs associated with the breadth and depth of openness outweigh the benefits, ultimately becoming detrimental (Laursen and Salter, 2006; Leiponen and Helfat, 2010; Capone and Innocenti, 2020). Researchers have discovered a nonlinear relationship characterized by an inverse U-shape between these two aspects of openness and innovative performance, leading to the identification of an optimal level.

In the light of the above studies, two other research hypotheses are therefore proposed:

H2a. The breadth will have a curvilinear relationship (taking an inverted U shape) with the innovation performance of Industry 4.0.

H2b. The depth will have a curvilinear relationship (taking an inverted U shape) with the innovation performance of Industry 4.0.

3. Methodology

3.1 Questionnaire

The following paragraph describes the questionnaire administered to approximately 600 Italian firms based in I4.0 clusters and specializing in I4.0 technologies, with the aim of investigating the role of openness of the innovative process in I4.0. In particular, the questionnaire was constructed starting from the CIS Survey carried out by the National Institute of Statistics (ISTAT) and the Report on I4.0 realized by Federmeccanica (2016) [1].

CIS data allow direct measurements of the innovative process and are often used in academic articles, especially in the economic field, which focuses on topics such as the determinants of innovation and the analysis of firms' performance (Smith, 2005).

Federmeccanica's research (2016) instead investigates the evolution of I4.0 among metal-working companies in Italy. It presents questions related to the adoption of technologies from the Fourth Industrial Revolution. In our questionnaires, specific questions have also been added on collaborations and OI in I4.0 that would allow the construction of some variables on collaborations, with particular reference to *breadth* and *depth* (Laursen and Salter, 2006; Leiponen and Helfat, 2010; Capone and Innocenti, 2020).

Subsequently, the questionnaire was tested, and a pilot study was conducted on a company operating in services related to new I4.0 technologies to refine it and adjust synthases. This first test was not included in the results.

LinkedIn Sales Navigator was therefore used with the aim of identifying target companies, with a likely focus on I4.0. To do this, a search was carried out using this LinkedIn tool using keywords related to the phenomenon under examination, such as "Industry 4.0", "Internet of Things", "Cloud Computing" and "Robotics" [2].

3.2 Characteristics of the sample [3]

The identified companies are Italian companies, mainly operating in the ICT and advanced manufacturing sectors that present the figure of a CTO (Chief Technology Officer) or responsible for 4.0 technologies. The questionnaire was administered by sending invitations to approximately 600 companies through LinkedIn, prioritizing employees with managerial roles (CTO, CEO, I4.0 managers, etc.).

Thus, 96 valid replies were received. The overall response rate was thus 16%, confirming a similar redemption rate in this kind of survey. A total of 88% of the responses come from qualified individuals within the companies [4].

The 96 companies are located throughout Italy in 14 different regions, mainly concentrated in the northeast-centre industrial triangle. A total of 58.3% of the sample focuses on information and communication technologies (ICT), while 9.4% belongs to the industrial automation sector. The remaining part of the sample (32.3%) concerns manufacturing sectors with a focus on activities not directly related to I4.0 technologies, such as the energy, mechanical, health care and automotive sector.

As far as company size is concerned, among the companies in the sample, those with less than 50 employees (micro and small enterprises) prevail, with a percentage equal to 66%. Medium-sized enterprises (between 50 and 249 employees) represent 14% of the sample and large enterprises represent 21% (with over 250 employees).

A total of 65% of the companies in the sample declare that they innovate in I4.0, and 89% of the companies in the industrial automation sector have innovated in this area. The percentage is 70% for companies in the ICT sector, while it drops to 48% for those in other sectors.

The main technologies in which the firms specialize are the Internet of Things, 77%, Big Data and Artificial Intelligence (both 66%) and Cloud Computing (56%). 3D printing is the technology on which companies focus the least.

Finally, 92% of the companies develop OI processes to innovate and establish collaboration with external innovation firms and research centres.

3.3 Data and variable construction

The dependent variable (*Innovation I4.0*) is given by the number of innovations relating to I4.0 technologies, a proxy of the innovative performance of companies in this field. This is determined by the number of different technologies to which innovation is connected and is a number between 0 and 9.

We choose as a proxy of innovation the number of I4.0 technologies in which a firm innovates, while in the literature, it is possible to find either the number of different technologies in I4.0 or the intensity of innovation in I4.0 (Büchi *et al.*, 2020; Bettiol *et al.*, 2023a; Capone and Innocenti, 2023) [5]. We prefer to use the first variable as it also counts the width of the innovation on I4.0 and permits us to consider technological scope economies.

The determinants of innovative performance in I4.0 are represented by the concepts introduced by Laursen and Salter (2006), which reflect the degree of openness to innovation of companies, namely, breadth (*breadth*) and depth (*depth*). In this research, the two variables refer to the ten different types of partners [6].

For the construction of these two variables, the methodology used by Laursen and Salter (2006) is followed. Starting from the *breadth*, each of the ten types of partners was considered as a binary variable, with a value of 0 or 1 if he/she had assigned any level of importance on the Likert scale. Subsequently, the binary variables were added.

Consequently, each company shows a *breadth* between 0 if it has not used any of the types of partners and 10 if it has collaborated with all the different sources of knowledge.

The *depth* was also built by forming a binary variable for each type of partner. However, a value of 0 was assigned not only to the case of "absence of partners", but also to the levels of importance 1, 2 and 3. The importance of the partners as a measure of the intensity of the collaborations with the partners was considered medium or low in these cases. If the respondents had assigned a type of partner with a high level of importance, equal to 4 or 5, the binary variables would instead have a value of 1. As for the *breadth*, the binary variables have been added. The *depth* of a company, therefore, assumes a value of 0 if there are no sources of knowledge with which it collaborates intensely, and a value of 10 if it collaborates deeply with all the different types of partners.

Some control variables are included in the model, including the variable *large*: measures the company size in terms of employees as a binary variable and assumes a value of 1 if the company is large (over 250 employees) or 0 otherwise. Because large companies have access to more financial and human resources, they may have greater innovative capacity.

Inn prod is a binary variable that reflects the type of innovation. It has a value of 1 if the company has introduced product innovations or 0 if it has not presented this type of innovation.

Inn Proc, like the previous one, has a value of 1 if the respondent company has introduced a process innovation, and 0 in the opposite case.

Partner cluster is a variable that reflects the level of geographical proximity of the partners. This facilitates knowledge flows and reduces the costs related to collaborations. To construct this variable, the question asking to indicate the location of the partners was considered. The ten different sources of knowledge were considered as binary variables, with a value of 1 if the company had presented a partner within the same cluster or 0 if it had not shown it. The variables were then added for each company.

As additional controls, to test a curvilinear relationship between openness and innovation in I4.0, the squared values of breadth and depth were also added ($breadth^2$ and $depth^2$). Finally, the relevance of the three innovations considered most transversal included *Big data*, *AI* and *IoT*.

Tables 1 and 2 present, respectively, the descriptive statistics and correlation matrix of the variables included in the models.

It is important to emphasize that it was not possible to build a variable relating to a company's R&D expenditure. To make up for this deficiency, a variable relating to the level

Variable	*N*	Mean	SD	Minimum	Maximum
Innovation I4.0	96	2.95	2.85	0	9
Breadth	96	4.58	4.17	0	10
Depth	96	1.93	2.42	0	10
Partner cluster	96	2	2.61	0	10
Inn. Prod	96	0.71	0.46	0	1
Inn. Proc	96	0.57	0.49	0	1
$Breadth^2$	96	38.16	39.75	0	100
$Depth^2$	96	9.51	18.44	0	100
Large firm	96	0.21	0.41	0	1
Big data	96	0.42	0.49	0	1
AI	96	0.42	0.5	0	1

Source: Our elaboration

Table 1.
Descriptive statistics

of internal competencies and capabilities related to Industry 4.0 was tested, but it was not significant in the regression models and therefore omitted.

A binary variable was also tested concerning the patenting activity of the respondents firms, but few firms realized patents in I4.0, so it was excluded from the analysis. Finally, binary variables relating to innovation in the different 4.0 technologies were tested.

4. Results and discussion

The characteristics of the dependent variable that are discrete and non-negative do not allow for the use of models assuming a normal distribution but require the use of estimation methods appropriate for count data (Hausman *et al.*, 1984) and, thus, fall in the area of the Poisson family.

Using the Poisson regression model requires that the mean of the data be restrained to be equal to the variance (Demidenko, 2013; Hilbe, 2011), which means Var $(Y_i) = \mathrm{E}(Y_i) = \mu$i. In this case, the strong variability of the number of patents called for additional tests on the over-dispersion of the dependent variable. Hence, we conducted a likelihood ratio test showing that the dependent variable is not overdispersed, thus suggesting the use of a Poisson estimator.

Prior to specifying the regression, we also tested for multicollinearity by performing a variance inflation factor (VIF) analysis showing maximum values [7] that are largely below the conservative cut-off value of 5 (Studenmund, 1992) or 10 as suggested by Neter *et al.* (1989), showing that multicollinearity is not a concern here.

The estimation of the models followed a stepwise approach. Table 3 reports the results of the Poisson regressions for the eight models.

The first model (Model 1) estimates the results only by including the two main variables of interest (breadth and depth) in investigating the effect of the openness of the innovation process on innovation in I4.0. Both variables show significant and positive results, suggesting that concerning breadth, an increase in the number of sources of knowledge favours an increase in innovative performances, while regarding depth, it suggests that developing relationships with a higher intensity favours the production of a higher number of inventions in I4.0.

Model 2 includes the control variables, the two variables regarding product and process innovation, the variable indicating the large dimension of the firm and the collaboration within the cluster. The results show that among the innovations, only process innovation is

	Variable	1	2	3	4	5	6	7	8	9	10
1	Breadth	1									
2	Depth	0.7210	1								
3	Partner cluster	0.1941	0.0200	1							
4	Inn. Prod	0.0554	0.0662	−0.1059	1						
5	Inn. Proc	0.1191	0.0701	0.0811	−0.0444	1					
6	Breadth^2	0.9731	0.7092	0.2260	0.0211	0.1344	1				
7	Depth^2	0.5251	0.9119	−0.0057	−0.0209	−0.0035	0.5528	1			
8	Large firm	0.1331	0.2393	−0.0691	−0.0094	−0.1275	0.1997	0.2499	1		
9	Big data	0.6314	0.5160	0.2513	−0.0019	0.0643	0.5558	0.3559	0.0756	1	
10	AI	0.6010	0.4985	0.0892	−0.0019	0.3197	0.5484	0.3260	0.0756	0.5743	1
11	IoT	0.7049	0.5322	0.1604	0.1833	0.1053	0.6273	0.3332	0.0001	0.6528	0.6107

Source: Our elaboration

Table 2.
Correlation matrix

Table 3. Poisson regression estimates the effects on I4.0 innovations

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8
Breadth	0.173*** (0.0275)		0.157*** (0.0286)	0.620*** (0.131)	0.715*** (0.131)	0.101*** (0.0308)	0.0936*** (0.0275)	0.0591* (0.0323)
Depth	0.0570* (0.0336)		0.0696** (0.0332)	0.107 (0.0891)	0.0313 (0.0916)	0.0347 (0.0266)	0.0519** (0.0229)	0.0600** (0.0268)
Partner cluster		0.0791*** (0.0288)	0.0305 (0.0216)		0.0529*** (0.0193)	−0.00277 (0.0183)	0.0467** (0.0208)	0.0219 (0.0179)
Inn. Prod.		0.318 (0.251)	0.200 (0.212)		0.130 (0.191)	0.216 (0.151)	0.252 (0.157)	−0.0510 (0.151)
Inn. Proc.		0.500** (0.221)	0.272 (0.190)		0.421*** (0.146)	0.286** (0.138)	−0.142 (0.152)	0.285* (0.153)
Breadth^2				−0.0427*** (0.0102)	−0.0536*** (0.0102)			
Depth^2				−0.00411 (0.00973)	0.00604 (0.00901)			
Large firm		0.403* (0.227)	−0.0190 (0.146)	0.187 (0.167)	0.332*** (0.129)	−0.0361 (0.109)	−0.0719 (0.129)	0.140 (0.112)
Big data						1.218*** (0.229)		
AI							1.259*** (0.214)	
IoT								1.494*** (0.351)
Constant	−0.140 (0.218)	0.256 (0.297)	−0.460* (0.270)	−0.850** (0.374)	−1.328*** (0.388)	−0.743*** (0.220)	−0.631*** (0.225)	−0.753*** (0.239)
Observations	96	96	96	96	96	96	96	96
Pseudo R^2	0.293	0.079	0.312	0.367	0.402	0.413	0.411	0.411
AIC	384.8	502.9	382.5	350.8	338.3	330.1	331.2	331.2
BIC	392.5	515.7	400.5	366.2	361.4	350.6	351.7	351.7
Log-likelihood	−189.4	−246.5	−184.3	−169.4	−160.1	−157.0	−157.6	−157.6
VIF average	2.08	1.01	1.46	15.52	10.76	1.57	1.58	1.69

Notes: Standard errors in parentheses; $*p < 0.1$; $**p < 0.05$; $***p < 0.01$
Source: Our elaboration

significant, with a positive effect on I4.0 innovation. While product innovation is not significant, the dimension of the firm seems to play a positive role in favouring innovation, as does the location of the partners closer to the firm, which appears to be an important driver of innovation in I4.0.

When we include the variables of interest within the same model with controls, as in Model 3, the breadth and depth retain their significance and positive effect on the innovative performance, while the control variables become all non-significant, meaning that there is an effect of the openness of the innovation that goes beyond the moderating effects of our controls, confirming both *H1a* and *H1b*.

Model 4 presents the variables of interest and the two squared values of the same variables. This is aimed at identifying the possible presence of nonlinear relationships between the openness of the innovation process and the innovation performance in I4.0. The results show a significant and positive effect for the variable *breadth* and a significant and negative effect for its squared value, meaning that there is an inverted U-shaped relationship. Consequently, the greater the number of different sources of knowledge from which companies draw, the greater the innovation in I4.0. However, there is a point where there are too many sources of knowledge that negatively affect innovation; thus, *H2a* is confirmed. While this relationship does not appear regarding the *depth*, both the first-order variable and the second-order variable are non-significant. For this reason, *H2b* is not confirmed, meaning that while regarding the breadth, the positive effect has a tipping point, regarding the depth, the positive relation is lower but seems to be linear.

Model 5 is the complete model presenting all the already discussed variables together. This is aimed at understanding if the inverted U-shaped relationship is robust to the introduction of our controls. The results confirm the inverted U-shaped relation among the number of external sources of knowledge and the innovation performance in I4.0, as well as the relevance of the cluster effect (proximity of the partners to the firm) and the dimension of the firm. Analysing this point more in depth, looking at Figure 1, it is possible to notice how the curvilinear relationship between breadth and innovation in I4.0 shows a tipping point of 7 different knowledge sources (70% of the possible sources). After this value, each additional knowledge source decreases the positive effect on innovation. The numbers are similar to those of Laursen and Salter (2006) and Leiponen and Helfat (2010).

Finally, the last three models (Models 6–8) are aimed at controlling for the relevance of specific types of innovations in I4.0. They are all three significant and positive underlining that those who innovate in those specific fields innovate more in I4.0, as these are transversal innovations that may benefit the whole capacity of the firm to innovate. What seems interesting is that even with the addition of these variables, the breadth maintains its significance sign in all models and the depth in two of the three models (7 and 8).

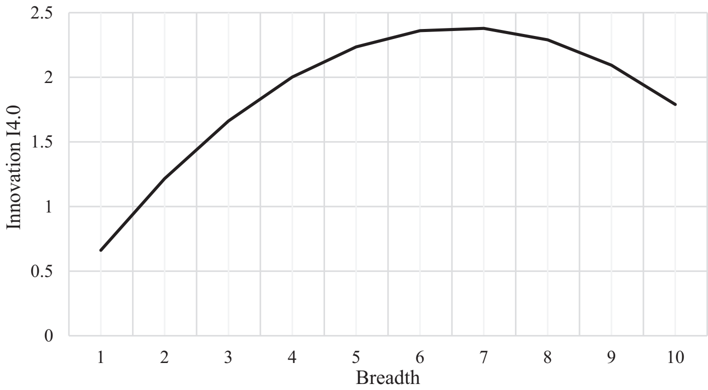
5. Conclusions

The aim of this article was to present empirical evidence regarding the innovation process in Industry 4.0, with a specific focus on the role of openness and collaboration in the Fourth Industrial Revolution. This led us to formulate the following research question:

RQ2. How do firms adopt open innovation dynamics for innovation in I4.0?

To address this question, we considered the concepts introduced by Laursen and Salter (2006) of *breadth* and *depth* as two dimensions that describe a firm's degree of openness to an external search strategy.

Companies demonstrate an increasing openness to knowledge from external sources for innovation, especially in the complex and interdisciplinary context of I4.0, where diverse



Source: Our elaboration

Figure 1. Curvilinear relationship between breadth and Innovation in I4.0

knowledge is required that may not be readily available within the company. Several authors have emphasized the significance of an open and collaborative culture in driving the development of digital innovations (Reischauer, 2018; Rocha *et al.*, 2019).

Previous studies suggested that greater breadth and depth led to enhanced innovative performance for companies investing in I4.0. Indeed, companies that leverage knowledge and new technological opportunities from a wide range of external sources tend to be more innovative than those solely relying on internal R&D efforts (Chesbrough, 2003; Laursen and Salter, 2006; Belderbos *et al.*, 2014). The research findings confirm this notion, indicating a positive relationship between breadth, depth and innovation in I4.0. Our contribution is based on the extension of the theory of breadth and depth of openness of external search strategy (Laursen and Salter, 2006) to the context of I4.0, which is a novelty of the paper. In fact, only a few papers have investigated the role of openness in external search strategies in the new context of I4.0 (Büchi *et al.*, 2020 and Ricci *et al.*, 2021).

The results of our analysis showed a clear and robust positive relationship between breadth and innovative performance in I4.0, and also a curvilinear effect inverted U-shaped is confirmed, thus *H1a* and *H2a* are confirmed. Regarding *H1b* and *H2b* concerning the relationship between the depth of the openness of the innovative process and I4.0 innovative performance, the results are less clear. We cannot confirm the inverted U-shaped relationship (2b), while regarding a positive linear relationship (1b), the results are positive and significant in a large part of the models but not always.

This confirms that the pursuit of external partnerships entails not only benefits but also costs. Costs arise from the absorption of external knowledge, as well as from timing challenges and the need for monitoring and control. Developing deep relationships with external partners can also result in organizational rigidity and dependence. Consequently, excessive openness, particularly in terms of breadth, can reduce the positive effect of additional external sources. The regression analysis results demonstrate an inverse U-shaped curvilinear relationship between these two components.

Industry 4.0's connectivity and data-driven management redefine innovation, yet they surprisingly adhere to an inverted U-shaped curve in external search strategy. While one might assume that the free flow of data and connectivity would eliminate such a curve, concrete cases demonstrate otherwise (Büchi *et al.*, 2020; Bettiol *et al.*, 2023a). Initially, as organizations embrace Industry 4.0, innovation flourishes with increased openness and collaboration. However, as openness peaks, it can lead to inefficiencies or security risks. Thus, Industry 4.0 challenges us to navigate this delicate equilibrium. Even in the digital age, where innovation thrives in a digitally connected world, openness should be carefully managed to harness its full potential.

The results of this article provide several important managerial implications for companies operating in the context of I4.0. The findings highlight the relevance of adopting an OI approach and leveraging external collaborations to drive innovation in this transformative era.

Firstly, the research confirms that embracing open and collaborative processes allows companies to seize a greater number of innovation opportunities and access knowledge about new technologies that may not be available internally. Therefore, managers of I4.0 companies should consider openness as a strategic response to the knowledge requirements and risks associated with the innovation process.

However, it is crucial for companies to approach OI in a mature, conscious and disciplined manner. This means not pursuing indiscriminate openness but rather efficiently and effectively managing a limited number of external knowledge sources. By doing so, companies can avoid dissipating their innovative efforts and maximize the benefits of external collaborations. Managers must carefully balance the breadth and depth of openness, taking into account the optimal levels that align with their specific organizational goals and context.

Furthermore, managers need to recognize that decisions regarding openness should consider additional factors. These factors include the collaborations with partners present in the cluster, the size of the company and the type of innovation being developed. Understanding how these factors influence innovative performance will enable managers to make informed decisions and tailor their OI strategies accordingly.

To select partners and knowledge sources, managers should follow a more structured process. Firstly, they should begin by aligning objectives and assessing the compatibility of potential partners. This involves defining clear goals and evaluating whether there are shared values and objectives. Secondly, managers should assess the expertise and resources of potential partners while conducting due diligence to minimize risks.

There are some limitations to this analysis that future research could address. For instance, the proposed analysis does not allow for an examination of the importance of breadth and depth for innovation within each individual source of knowledge. Future research could explore the relationship between breadth, depth and innovative performance within each knowledge source, as well as evaluate which sources are most significant for innovation in Industry 4.0. Moreover, while other studies on I4.0 used as an innovation variable the I.4 intensity of innovation (Bettiol *et al.*, 2023a; Büchi *et al.*, 2020), we chose as a proxy of innovation the number of adopted I4.0 technologies. Therefore, our results should be carefully compared to those of other studies. However, in our opinion, the analysis shows similar results, increasing the robustness of the inverted-U shape relation in I4.0.

Additionally, because of inaccurate responses, the effect of R&D spending could not be evaluated in this model. Obtaining reliable answers and incorporating them into the model would be of interest.

Notes

1. Trade union association of the Italian Mechanical Industry.
2. The keywords refer to the different technologies that can be included in the I4.0 evolution: "Industry 4.0", "Cyber-Physical Systems", "Internet of Things", "Artificial Intelligence",

"Augmented Reality", "Cloud Computing", "Big Data", "Robotics", "Additive Manufacturing", "Cyber Security", "Smart Factory", etc. See Lazzeretti *et al.* (2022).

3. We included some descriptive statistics of the sample as supplementary material (see Appendix).
4. Out of these, 32% are CEOs, 27% CTOs and the remaining percentage are other executives at the C-level, including innovation managers.
5. Bettiol *et al.* (2023a) and Büchi *et al.*, 2020, differently from this study, use the numbers of different technologies adopted in I4.0 to construct the depth and breadth variables. Moreover, Bettiol *et al.* (2023a) then use as innovation variable the innovation intensity of the firm, while Büchi *et al.*, 2020 consider the firm's perceived opportunities.
6. The analysis includes suppliers, clients or customers, competitors (in or outside the same industry), consultants, commercial laboratories/R&D enterprises, universities or other higher education institutes, government research organizations or private research institutes/startups.
7. Excluded the models with the addition of the squared terms, where the values are frequently higher.

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Further reading

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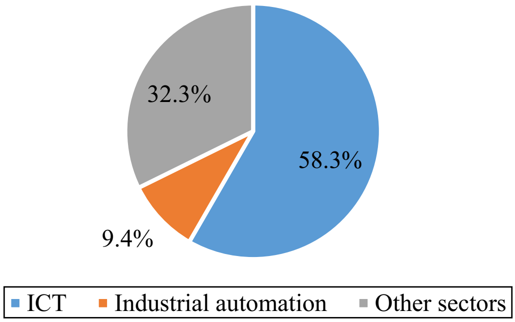
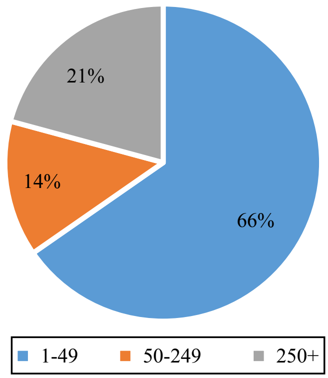
Appendix. Summary statistics of the sample



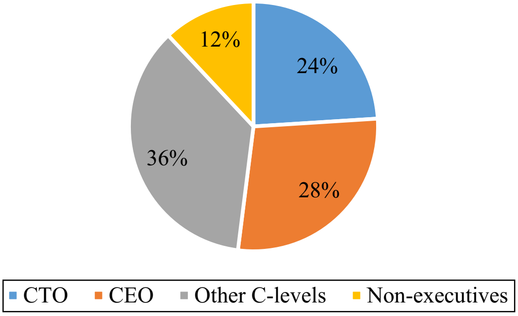
Source: Our elaboration

Figure A1. Primary industry sector of the companies in the sample



Source: Our elaboration

Figure A2. Dimensions of the companies (employees)



Source: Our elaboration

Figure A3 Role of the respondents

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