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Industry 4.0 as an Enabler of Open Innovation

Serena Strazzullo, Benito Mignacca, Michele Grimaldi, Marco Greco, and Livio Cricelli

Abstract—**A growing body of literature surrounds Open Innovation (OI) initiatives and Industry 4.0 (I4.0) technologies. However, despite the growing interest by academics, practitioners, and policymakers in both domains, the link between the two remains underinvestigated from an empirical point of view. This article addresses this gap in knowledge by leveraging 16 semistructured interviews with practitioners involved in both the I4.0 context and OI initiatives. This article provides two main contributions. First, it identifies a series of I4.0 technologies (e.g., Big Data, advanced manufacturing) enabling OI initiatives (e.g., crowdfunding, cocreation). Second, it identifies and examines the benefits and challenges of adopting such I4.0 technologies. The benefits include improved data management, reduced time to market, improved production phase, and increased client satisfaction. The challenges include the lack of capabilities, resistance to change, and security issues. The exploratory nature of this study triggers exciting future research opportunities about OI initiatives and I4.0 technologies.**

Index Terms—**Digital transformation, digitalization, Industry 4.0 (I4.0), innovation management, open innovation (OI).**

I. Introduction

CURRENT economic scenarios are constantly evolving, bringing new production (e.g., additive manufacturing, augmented reality) and information and communication technologies (e.g., Big Data, artificial intelligence). These technologies, which pertain to the Industry 4.0 (I4.0) domain, determined significant changes in innovative processes, triggering new mechanisms for interacting with and benefiting from the surrounding environment [1], [2]. The I4.0 can be conceptualized as an industrial stage characterized by the integration of manufacturing systems and information and communication technologies [2], [3]. Examples of I4.0 technologies include [4]: artificial intelligence, augmented/virtual reality, Big Data, blockchain technologies, cloud computing, digital platforms, and the Internet of Things. I4.0 technologies assist companies in transforming their activities and improving internal efficiency and innovation [5]. Companies often resort to external organizations in order to fully benefit from such technologies [6], [7].

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We advance that the resulting interorganizational collaborations can be analyzed through the lenses of the Open Innovation (OI) paradigm [8]. OI is defined as a model of open, collaborative, and distributed innovation [9]. According to the OI paradigm, knowledge flows between two or more organizations (e.g., suppliers, customers, competitors, R&D institutions) can foster innovation. The literature about OI emphasizes the benefits of this paradigm, such as reducing development costs and time to market, along with enhancing the know-how of a firm [10], [11], [12], [13]. Examples of OI initiatives include [4]: collaboration, crowdfunding, cocreation, crowdsourcing, customer immersion, merger & acquisition, and operations in open business models.

Therefore, on the one hand, I4.0 technologies can influence knowledge flows between organizations and the associated business models, processes, and products. On the other hand, OI practices can serve as knowledge brokers and sources, assisting firms in their digital transformation [14].

Academics are increasingly discussing the synergies between I4.0 technologies and OI domains [15], [16], [17]. For instance, Pénin et al. [18] point out how digital technologies can facilitate the identification of partners and the development of collaborations. Wallin and Von Krogh [19] highlight that information and communication technologies and connectivity play a relevant role in rising new approaches, such as hackathons, innovation challenges, and crowdsourcing. Moreover, Barlatier et al. [20] provide a framework integrating several digital technologies (e.g., Big Data, cloud computing, artificial intelligence) through the stages of the OI process.

Despite the growing academic interest, the empirical evidence about the link between I4.0 technologies and OI initiatives is still limited [4]. Indeed, Urbinati et al. [16] invited researchers to deepen the link between OI and digital technologies through empirical studies. Furthermore, Bigliardi et al. [21] highlighted the relevance of exploiting the impact of I4.0 technologies on the OI paradigm, along with the need for further research. Additionally, as highlighted by Strazzullo et al. [4], the studies about I4.0 technologies and OI initiatives examine links between "specific" I4.0 technologies and OI initiatives, and there are no studies investigating the link between I4.0 and OI embracing a "holistic" perspective. This article aims to address this gap in knowledge by holistically investigating the link between I4.0 technologies and OI initiatives in the manufacturing sector. Therefore, the holistic perspective (i.e., not limited to specific links) in analyzing the link between I4.0 technologies and OI initiatives is the key element of novelty of this article. The unit of analysis is the relationship between I4.0 technologies and OI initiatives. The embedded unit of analysis is the elements influencing the implementation of I4.0 technologies enabling

OI initiatives. In particular, we formulated the following two research questions (RQs).

RQ1: Which I4.0 technologies enable OI initiatives?

RQ2: Which factors influence the implementation of OI enabling technologies?

The aforementioned RQs were addressed by leveraging 16 semistructured interviews with practitioners with relevant experience in both adopting I4.0 technologies and implementing OI initiatives in the manufacturing sector. By leveraging a thematic analysis of the data collected, this article provides two main contributions. First, it identifies a series of specific links between I4.0 technologies and OI initiatives. Second, it identifies and examines the benefits and challenges for the implementation of such I4.0 technologies enabling OI initiatives. The benefits identified and examined are improved data management, reduced time to market, improved production phase, and increased client satisfaction. The challenges identified and examined are lack of capabilities, resistance to change, and security issues. The findings of this article contribute to the body of knowledge at the intersection between I4.0 and OI innovation domains by presenting and examining the role of I4.0 technologies in enabling OI initiatives. It can be categorized as theory-building research [22]; indeed, relationships about I4.0 technologies and OI initiatives, along with constructs about the elements influencing those I4.0 technologies, have been identified. Regarding the practical implications, the findings of this article are relevant for companies involved in one of the two domains (OI or I4.0) to consider, for instance, which I4.0 technologies foster OI initiatives, along with the factors influencing the adoption of the identified I4.0 technologies.

The rest of the article is structured as follows. Section II presents an overview of the domains investigated in this article (i.e., OI and I4.0) and their link. Section III summarizes the main steps of the methodology adopted. Sections IV and V present and discuss the findings, respectively. Finally, Section VI concludes the article and suggests future research opportunities.

II. Literature Review

A. Overview of OI

Chesbrough [8] introduced the concept of OI, highlighting how the creation of knowledge is linked to an open vision of the organization. Chesbrough's insights triggered a relevant stream of research about OI. For instance, Gassmann et al. [12] expanded the concept of OI, pointing out the importance of patents and intellectual property in OI models. Chesbrough and Bogers [23] provided a new definition of OI by adding the economic perspective to the concept: "Open innovation is a distributed innovation process based on purposively managed knowledge flows across organisational boundaries, using pecuniary and non-pecuniary mechanisms in line with each organisation's business model" (p. 24). Afterward, Bogers et al. [24] introduced new layers to the OI model, expanding the traditional analysis at the organizational level to a multiple-level OI analysis. In the last decades, several articles systematically categorized the literature about OI [25], [26], [27], [28], [29], [30]. Among these, a seminal article is [25], which provides a novel conceptual model for OI.

TABLE I
OI Practices

OI practices	Brief description	Ref.
Co-creation	The joint work of the company and customers in creating value	[38]
Collaborative problem-solving and product design	A process that includes two or more actors who attempt to solve a problem by sharing their knowledge, skills and efforts	[39]
Crowdfunding	A form of venture capital financing targeting a large and indeterminate group of people	[40]
Customer immersion and customization	A collaborative innovation practice that aims to capture the value from the customer directly or indirectly through an immersive experience	[4]
Networking	An organizational contribution to a larger ecosystem in which each participant nourishes the activities of others with their own knowledge	[41]
Operation in open business model	A collaborative approach that breaks down organizational boundaries for knowledge sharing. It considers the combination of innovation and technology as the origin of value creation, driven by a continuous flow of interactions with external actors	[42]

In particular, the authors merged the concept of openness as traditionally conceptualized by Chesbrough [8] (i.e., considering the different types of opening, inbound and outbound) with a second dimension related to the interaction mechanisms (i.e., pecuniary or nonpecuniary) between the actors involved. A key novelty lies in bringing down the dichotomy between OI and closed innovation, considering the opening as a continuum. Additionally, Gao et al. [28] proposed a more comprehensive and structural framework for the OI. The framework considers different types of innovation processes according to three different steps for knowledge sharing and transfer (i.e., acquisition, integration, and commercialization of innovations). Furthermore, several articles focused on the benefits and enabling factors of OI initiatives [31], [32], [33], [34], [35], [36], [37]. Regarding the benefits, Bonfanti et al. [31] highlighted how implementing OI initiatives allowed small- and medium-sized enterprises to reduce the time to market and innovation costs, along with the opportunity of sharing risks with partners. Moreover, Ooms and Piepenbrink [33] first stressed the strategic role of OI to solve complex or wicked problems and second highlighted how partners leverage their differences to improve service innovation. Regarding the enabling factors, Sağ et al. [32] pointed out the relevant role of external factors (e.g., government programs, regional innovation policies, and intellectual property protection mechanisms) in the choice of implementing OI initiatives. Moreover, Cillo et al. [35] analyzed OI in agri-food businesses, showing how information technology (IT) based knowledge exploitation capabilities enabled OI initiatives. A recent study cross-referenced the OI process dimension with the one related to the exploitation of digital technologies [4]. The combination highlighted several OI practices that can be implemented in combination with specific digital technologies. Table I presents an overview of such OI practices.

B. Overview of I4.0

There is a lack of an agreed-upon definition of I4.0, posing limitations to theory building and comparison among studies [43]. It is often defined as "the set of technologies, devices and processes that allow for self-sufficient production models, capable of operating in an integrated way along the several phases of the production process and along the several levels of the supply chain and able to make decentralised decisions with minimum human intervention" [44, p. 2]. Moreover, the term I4.0 is often referred to as the fourth industrial revolution, arising from a German public-private initiative aiming to build smart factories by integrating physical objects with digital technologies [45]. The introduction of digital technologies led to a new industrial phase characterized by the connectivity of integrated production systems [46].

The novel production systems allow real-time information sharing (often without human involvement) throughout the supply chain, ultimately reducing complexity and improving process efficiency [47]. In the I4.0 context, devices and machines are connected and communicate using different I4.0 "Key Enabling Technologies," i.e., knowledge-intensive technologies (e.g., advanced materials, advanced manufacturing) supporting the development and deployment of connected and integrated systems [48]. Xu et al. [49] reviewed the literature about the implementation of I4.0 technologies, highlighting how the lack of adequate systems and formal methods, along with other technical challenges (e.g., inadequate ICT infrastructure, scalability issues), can hinder the adoption of I4.0 technologies. Frank et al. [50] focused on the I4.0 implementation patterns in manufacturing companies, ultimately providing a maturity model showing technology patterns. A key takeaway is a relationship between I4.0 and the systemic adoption of front-end technologies, where smart manufacturing plays a pivotal role. Furthermore, Kristoffersen et al. [51] emphasized the relevant role of I4.0 technologies in implementing circular economy initiatives and provided a "digital-enabled circular strategies framework" for manufacturing companies. Additionally, several studies highlighted how the I4.0 field is expanding and that there is a need for creative business models analyzing the influence of I4.0 technologies in creating value [52], [53]. Table II summarizes relevant I4.0 technologies that can be adopted in organizational innovation processes.

TABLE II
I4.0 TECHNOLOGIES

I4.0 Technologies	Brief description	Ref.
Advanced manufacturing	Integration of techniques and additive technologies to optimize the design and production process	[54]
Artificial intelligence	Technology that allows machines to be endowed with certain characteristics that are considered typically human	[55]
Augmented reality	Technology that allows users to enrich the view of real environments by inserting virtual objects	[56]
Big data	Large amounts of data for predictive applications that traditional databases cannot handle due to the large volume and the presence of raw and unstructured data	[57]
Cloud computing	A set of ICT services accessible on demand and in self-service mode via Internet technologies, based on shared resources, characterized by rapid scalability and punctual measurability of service levels	[58]
Connectivity	Machine-design aspect related to the process of transferring data between edge devices (sensors or controllers) to other devices or to the cloud	[59]
Digital platforms	Digital infrastructures that connect different systems, presenting them to users via simplified and integrated interfaces, usually a mobile app or a website	[60]
Internet of things	System to generate networks of automated intelligent devices capable of sharing knowledge, transmitting, data, and responding to external environmental stimuli	[61]
Robotics	Technology with a wide range of manufacturing-related capabilities. It often improves automated systems, performing repetitive tasks accurately and cost-effectively	[62]
Social media platform	Platforms for the dissemination of speeches, opinions, information, or other content to the public	[63]

C. Linking OI Initiatives and I4.0 Technologies

In the last decade, I4.0 technologies significantly reshaped the processes of several industries.

This revolution transforming the industrial sector can be conceptualized as an open model, which starts from digitization and integrates all the new technologies coming from the IT world and beyond. The latest trend is a new concept of OI, which can be expressed as "OI 4.0" or "digital OI." The widespread adoption of digital technologies in innovation processes prompted management and innovation experts to develop new open digital technology management theories [24], [64]. According to Sjödin et al. [65], the discovery, selection, and execution of customized digital strategies in line with innovation efforts are primary concerns for organizations. Several studies in the literature show a relationship between OI strategies and digital technologies. In particular, the selection of potential partners and the development of cross-border interactions are facilitated by digital technologies; they enable businesses to establish successful systems for including external collaborators in internal operations [18]. Furthermore, online innovation tools [66], which are targeted at involving users, are considered among the most valuable external sources of knowledge for innovation [67]. Additionally, Yoo et al. [68] pointed out that the OI paradigm is an effective model for exploiting the benefits of digital technologies. Berente et al. [69] first presented a theoretical framework including the different approaches driving distributed innovation. Second, the authors suggested further investigating the transition from traditional business models to business models supporting open digital innovation. In the context of I4.0, there is a growing interest in those OI practices that use digital technology as an enabling element, such as crowdsourcing and cocreation [70], [71], [72], [73], [74], [75].

In summary, on the one hand, companies often resort to external organizations to implement and benefit from I4.0 technologies. As aforementioned, we advance that the resulting

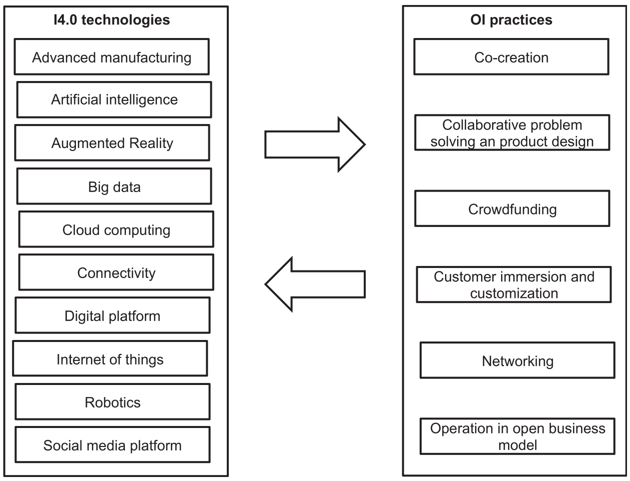

Fig. 1. Conceptual model.

interorganizational collaborations can be analyzed through the lenses of the OI paradigm. On the other hand, OI practices can be enabled or facilitated by I4.0 technologies.

However, as highlighted by Strazzullo et al. [4], the studies about I4.0 technologies and OI initiatives examine links between "specific" I4.0 technologies and OI initiatives. Remarkably, there are no studies investigating the link between I4.0 and OI embracing a "holistic" perspective. This article addresses this gap in knowledge by holistically investigating the link between I4.0 technologies and OI initiatives. In particular, this article empirically examines the relationship between I4.0 technologies and OI practices, as presented in the conceptual model in Fig. 1.

III. Methodology

A. Research Approach, Data Collection, and Sampling Strategy

The authors adopted an abductive approach in investigating the link between I4.0 technologies and OI initiatives. In abductive research, known premises are used to define testable conclusions. The abductive approach is appropriate for exploring a phenomenon and identifying themes and patterns [76]. Two main factors motivated the choice to adopt an abductive approach: 1) the exploratory nature of this research at the intersection of the OI domain and I4.0 domain, and 2) the relevant literature about the two single domains that we leveraged to investigate the phenomenon. Indeed, we leveraged a predefined list of I4.0 technologies and OI initiatives in initiating the interview process, as shown in Fig. 1.

Data were collected through semistructured interviews in order to ask follow-up questions or comments [77], [78]. A purposive sampling strategy guided the selection of the interviewees [79]. In particular, three criteria guided the selection: 1) employed by a company with relevant experience in the implementation of I4.0 technologies, 2) at least ten years of experience in the manufacturing sector, and 3) sufficient expertise in OI practices. A total of 16 interviews were collected between April and June 2021; details of the interviewees are presented in the

TABLE III
Example of the Coding Process—Layout Adapted From [78] and [85]

Extract from the interviews	Preliminary coding (nodes)	Final coding (sub-themes)	Final coding (themes)
The adoption of I4.0 technologies allowed to improve the exchange of information among workstations	Improved exchange of information among workstations	Improved data management	Benefits
Regarding production and quality, we applied in these contexts the collection of big data, therefore all the information about the performance of production plants. By leveraging such data collection, we are able to obtain information about the good quality components and conduct analyses about the production losses	Better information about production performance		
The most relevant benefit determined by I4.0 technologies was higher client satisfaction because, in addition to improving the product, we were able to offer better and less expensive service	Better and less expensive service leading to higher client satisfaction	Higher client satisfaction	
3D printers supported initiatives of customization and customer Immersion, allowing to give something more substantial to the client and to have an added product on his customization	Advanced manufacturing supporting customization and customer immersion		

Appendix (see Table IV). The authors stopped the data collection process when data saturation was reached, i.e., when data were clear to the authors and redundant to address the RQs [80]. The average length of the interview was 44 min. The interviews were conducted in Italian via digital platforms (e.g., Microsoft Teams, Skype). Table V in the Appendix shows the final semistructured questionnaire used as a basis for dialogue.

B. Data Analysis

The interviews were analyzed through thematic analysis, i.e., "a method for identifying, analysing and reporting patterns (themes) within data" [81, p. 79]. The researcher does not relate frequency with importance in conducting a thematic analysis but focuses on the links between the emerged themes and the RQs [82]. Following a verbatim transcription of the interviews that resulted in 61 pages, one of the authors conducted the coding process. Several discussions among the authors led to the final classification of themes and subthemes. NVivo version 12, a computer-assisted qualitative data analysis software, was used only to support the categorization of the information in themes and subthemes. The software did not play a relevant role in the analysis per se; we leveraged the software to categorize the information in the transcripts into nodes, subthemes, and themes. As recommended by Saldana [83], a two-step coding process was followed: 1) summarizing in a few words each relevant section, which represents a theme or subtheme (nodes); and 2) reorganizing the list of nodes in themes and subthemes based on similarities. In other words, the researcher involved in the coding adopted three coding approaches [84]. First, the researcher adopted an open coding approach, i.e., the nodes were identified by leveraging the description of the interviewees. Second, an axial coding approach was adopted to identify the relationships between the different nodes by further examining the transcripts associated with each node. Last, a selective coding approach was followed to identify "themes" linking the identified subthemes. Table III reports an example of the coding process.

The analysis led to the definition of I4.0 technologies enabling OI initiatives (summarized in Section IV-A) and the benefits and challenges of such I4.0 technologies (summarized in Section IV-B).

C. Data Analysis

The authors ensured the reliability of the findings concerning RQ2 by following and adapting the approach developed by Whitman and Woszczynski [86] and recently employed by Sainati et al. [87]. In particular, the following set of questions, extracted and/or adapted by Sainati et al. [87], was used to test three areas of reliability criteria.

1) Representativeness of findings (confirmability).
   a) Considering the different sources of the data collected and analyzed, were the findings cross-confirmed?
2) Reproducibility of findings (dependability/audibility).
   a) Was the method described in detail?
   b) Was the method followed in detail?
   c) Was the reflexive process described with sufficient detail?
3) Rigor of method (internal consistency).
   a) Was the empirical evidence sufficiently connected to the research results?
   b) Was the abductive process sufficiently explicit?

We leveraged these questions throughout the research process in order to ensure the reliability of the findings.

IV. Findings

A. I4.0 Technologies Enabling OI Initiatives

First, interviewees highlighted specific links between I4.0 technologies and OI initiatives. Fig. 2 summarizes the links

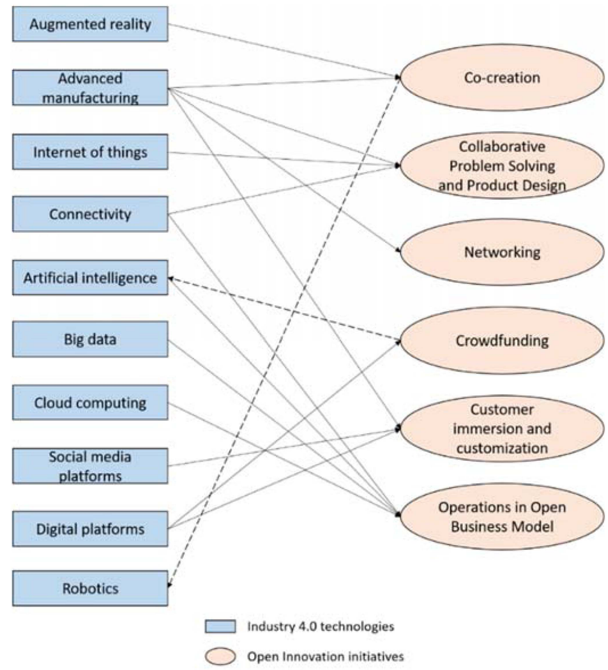

Fig. 2. I4.0 technologies enabling OI initiatives.

between I4.0 technologies and OI initiatives mentioned by the interviewees.

Second, in some cases, the interviewees highlighted "how" I4.0 technologies can enable OI initiatives. Regarding the "how," Interviewee 03 stated: "Advanced manufacturing, additive manufacturing, Internet of Things, and connectivity favoured initiatives of collaborative problem solving through collaborations with universities and start-up [...]. Advanced manufacturing certainly supported the initiative of collaborative problem solving and product design because it allowed us to exchange an incredibly huge amount of information at high speed; this was not possible before [...]. Advanced manufacturing also supported the networking because the speed at which we received the data facilitated any collaboration." Interviewee 10 focused on digital platforms, highlighting that they "contributed to the exchange of structured information; therefore, they had a relevant role for the crowdfunding both regarding the security, but also to ensure a structured data flow with elements that can guarantee workflows and procedures."

These findings are in line with those of Mubarak and Petraite [88], who emphasized how the implementation of I4.0 technologies can serve as an efficient mechanism for optimizing the OI network. In particular, Mubarak and Petraite [88] highlighted how I4.0 technologies can facilitate cocreation, collaboration, and partnership by emphasizing the significance of data sharing, communication, and computation as fundamental components.

Moreover, Interviewee 07 argued: "We are much more reactive in presenting the samples to the client and to have confirmation that what the client has seen in a PowerPoint presentation or in rendering is what he effectively wants." Interestingly, two interviewees highlighted the reverse link, i.e., an OI initiative as an enabler of one of the I4.0 technologies. Interviewee 07 argued:

"The crowdfunding [...] is a practice that we adopted before Industry 4.0 technologies, and one of the technologies that can be associated with this practice could be artificial intelligence, for which we are receiving substantial investments." Moreover, Interviewee 02 stated: "The opportunity to use these novel technologies [...] has been possible through the collaboration with the Technological Institute X, which is expert of robotics [...]. It is essential working together and [...] the entire organisation has to be keen to collaborate."

B. Factors Influencing the Adoption of the Identified I4.0 Technologies

The thematic analysis led to the identification of two themes (benefits and challenges) and seven subthemes. The "benefits" theme includes four subthemes: improved data management, reduced time to market, improved production phase, and increased client satisfaction. The "challenges" theme includes three subthemes: lack of capabilities, resistance to change, and security issues.

1) Benefits:

a) Improved data management: A relevant benefit determined by the I4.0 technologies is the improvement of data management. Interviewee 03 highlighted how: "The areas where we use Industry 4.0 technologies are Production, Quality and R&D. Regarding Production and Quality, we applied in these contexts the collection of Big Data, therefore all the information about the performance of production plants. By leveraging such data collection, we are able to obtain information about the good quality components and conduct analyses about production losses." Moreover, Interviewee 07 argued: "The collection of these Big Data allowed us to analyse the data coming from sensors that we installed on some systems, such as security cameras, temperature, height, and dimension sensors; [...] these Big Data allow to conduct simulations on the lifetime of systems and some pieces of machinery." This evidence is in line with [89], which discusses how emerging IT holds immense potential for manufacturing enterprises in enhancing data processing efficiency and facilitating integration between equipment and production lines.

b) Reduced time to market: Another key benefit mentioned by the interviewees is the reduction of the time to market. On this matter, Interviewee 07 argued: "Regarding research and development, the most relevant [...] benefit has certainly been the reduction of product development time, because we are much more reactive in presenting the samples to the client and having a confirmation [...]; we can penetrate the market more quickly [...]. Research and development hours have been reduced; we moved from a 14–18 months schedule to a 6–7 month schedule." Previous studies also showed a reduction in time to market; however, it was generally linked to the reduction of lead times and as a consequence of the improvement in the automation of activities [90], [91].

c) Improved production phase: The interviewees highlighted the improvement of the production phase as one of the major benefits determined by the I4.0 technologies reported in Fig. 2. For instance, Interviewee 07 stated: "We noticed an increased efficiency and a reduction of the scraps, [...] a reduction of production losses due to the maintenance; [...] intervening preventively and not after the breaking point [...] reduces the production losses due to the wait for a spare part." Interviewee 01 provided a broader perspective, pointing out that "such technologies allow a better business process management; in particular, a better warehouse and working phase management. Therefore, the most relevant benefit is certainly increasing the business efficiency." Moreover, Interviewee 12 stated: "A benefit determined by these technologies is certainly higher productivity; in fact, we found that the operator had an improvement of 20–30% by those systems. Also, the mistakes drastically reduced." Interviewee 13 focused on the safety aspect of the production phase, arguing: "We introduced a robot [...] to verify the temperature [...] and introduced a camera in the furnace which allows verifying the internal conditions of the furnace. I carried out this activity by standing in front of [..] the furnace for some seconds, but it was always a risky condition and a very subjective analysis. Thanks to these robots, we can safely analyse the images taken inside the furnace [...]; there is greater precision in the decisions [...]. Therefore, in terms of safety, these robots allowed to obtain more objective and less risky analysis." This finding is in line with previous contributions that examined how I4.0 technologies are essential for achieving the objectives of efficiency and effectiveness in the production phase [92], [93].

d) Increased client satisfaction: Interviewees argued that OI enabling technologies also increase client satisfaction, stressing the reasons behind such an increase. For instance, Interviewee 06 stated: "The most relevant benefit determined by Industry 4.0 technologies was a higher client satisfaction because, in addition to improving the product, we were able to offer better and less expensive service." On this matter, Interviewee 07 pointed out: "3D Printers supported initiatives of Customisation and Customer Immersion, allowing to give something more substantial to the client, and to have an added product on his customisation." On this matter, a study by Ali et al. [94] showed how the main benefits of these technologies are customization and personalization, even in mass production.

2) Challenges:

a) Lack of capabilities: A relevant challenge mentioned by the interviewees is the lack of capabilities, which could hinder the adoption of the identified I4.0 technologies. The interviewees mostly stressed digital capabilities. For instance, Interviewee 04 stated: "If we look at the challenges [...], one was related to human resources, which were not prepared at the managerial level, given that digital training is different with respect to the conventional one." The interviewees suggested two main remedies to overcome the lack of capabilities: 1) training of the employees and 2) new hires. Regarding the training, Interviewee 05 stated: "We had to substantially invest in the reorganisation of work because our procedures changed substantially both in the design and production perspective; therefore, we had to invest considerably in training." Regarding the new hires, Interviewee 02 argued: "In order to analyse the data coming from the robots, [...] ultimately we realised that we did not have those capabilities internally, we started [...] to include

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data scientists in our staff." Although the lack of capabilities (digital in particular) represents a relevant challenge to the development and deployment of I4.0 technologies, according to the interviewees, they also represent an opportunity to improve the corporate culture. On this matter, Interviewee 02 highlighted: "Certainly, there was an improvement of the corporate culture because the digital transformation implies the opportunity to share knowledge and skills that people have about products and processes." This challenge was also identified by Tay et al. [95]. In order to overcome this challenge, Tay et al. [95] suggest that firms must be extremely agile and establish a high level of resilience, management competencies, and structural flexibility.

b) Resistance to change: The resistance to change is also a major challenge. On this matter, Interviewee 01 stated: "As in all innovation projects, there is always the resistance to change to some extent [...]; although things turn out simpler over time, more optimised, the initial reaction is always that of the resistance." Furthermore, Interviewee 16 pointed out: "The major problem was the involvement of different actors of several workstations because there are often experienced people, but they do not have the mindset ready for the Industry 4.0." Interviewee 02 focused on the remedies to the resistance to change: "The first challenge was to bring the digital transformation in the entire organisation [...]. The Chief Executive Officer and the top management had an essential role in leading by being a good example [...]; I was nominated Chief Digital Officer, aiming to lead my colleagues towards digitalisation. Afterwards, the change management disseminated the digitalisation culture." These results are consistent with Raj et al. [96], who stressed how the resistance of employees hinders the implementation of activities and adds unforeseen costs that could jeopardize the digital transformation process of an organization.

c) Security issues: The theme of security (in particular from cyber-attacks) was often stressed by the interviewees, however, with controversial views. For instance, Interviewee 16 highlighted: "Another challenge is certainly cyber security because we have to adapt to new regulations continuously." Interviewee 05 pointed out how the cyber security risks depend on the dimensions of the companies, stating: "Regarding the theme of cyber security [...], if we talk about small and medium-sized enterprises, there are no big risks. The security needs to be related to the dimension of the company," whereas Interviewee 06 does not consider the theme of cyber security as an issue: "Regarding the theme of cyber security, we did not find any difficulty [...]. Most of the services related to Industry 4.0 include security, while you had to build it in-house in the past." Previous contributions also stressed how cyber-attacks might target information sharing and inventory management in a digitalized supply chain with automated and linked systems [97], [98].

V. Discussions

The research presented in this article addressed two RQs.

RQ1: Which I4.0 technologies enable OI initiatives?

RQ2: Which factors influence the implementation of OI enabling technologies?

The following two sections discuss the findings related to each RQ.

A. RQ1: Which I4.0 Technologies Enable OI Initiatives?

Fig. 2 in the previous section summarizes the responses of the interviewees with respect to RQ1. Most interviewees agreed on the enabling role of I4.0 technologies in implementing OI initiatives and highlighted specific links between I4.0 technologies and OI initiatives. The next part of this section discusses the highlighted links, comparing them with the existing literature. In particular, the interviewees pointed out the following links for each OI initiative that was mentioned.

1) Cocreation: Advanced manufacturing and augmented reality play a relevant role in favoring cocreation initiatives. The client plays a vital role in creating value in cocreation [38], and advanced manufacturing can improve the control of value-creation processes. Augmented reality is also a crucial tool since producers and customers can engage more easily. Additionally, Chi et al. [99] pointed out other I4.0 technologies supporting cocreation initiatives, i.e., Internet of Things and digital platforms. Moreover, the interviewees highlighted the reverse link, i.e., cocreation initiatives supporting the adoption of I4.0 technologies, specifically robotics. The reverse link is also highlighted by Pedersen [100] in the public sector.

2) Collaborative Problem-Solving and Product Design: Collaborating problem-solving and product design can be supported by the following I4.0 technologies: connectivity, advanced manufacturing, and the Internet of Things. Connectivity tools can allow companies to monitor, analyze, and control remote devices, thereby facilitating collaboration among the actors involved in innovation projects. The introduction of advanced manufacturing can speed up the prototyping phase, smoothing the collaboration activities. The Internet of Things can support collaboration by improving interaction. According to Aleksandrova et al. [101], blockchain technologies also represent a relevant factor in enabling collaborative problem-solving and product design by guaranteeing security and transparency of the process. This assumes a higher relevance in the case of business processes involving mutually unreliable parties in a decentralized environment.

3) Networking: Advanced manufacturing can also support the initiatives of networking by increasing the speed of information exchange, thereby favoring collaboration initiatives. Moreover, advanced manufacturing systems are being used as time-based competition weapons, taking advantage of economies of scope and speed of action and enabling collaboration across the value chain and industry boundaries. Other I4.0 technologies that can be relevant from an OI perspective but did not emerge from the interviews are digital platforms, which can facilitate networking across the value chain and industry boundaries [102], and blockchain technologies, which can increase the security of the transactions in the network [17].

4) Crowdfunding: The interviewees pointed out the pivotal role of digital platforms in supporting crowdfunding initiatives. This is also stressed by Strazzullo et al. [4], which argue that

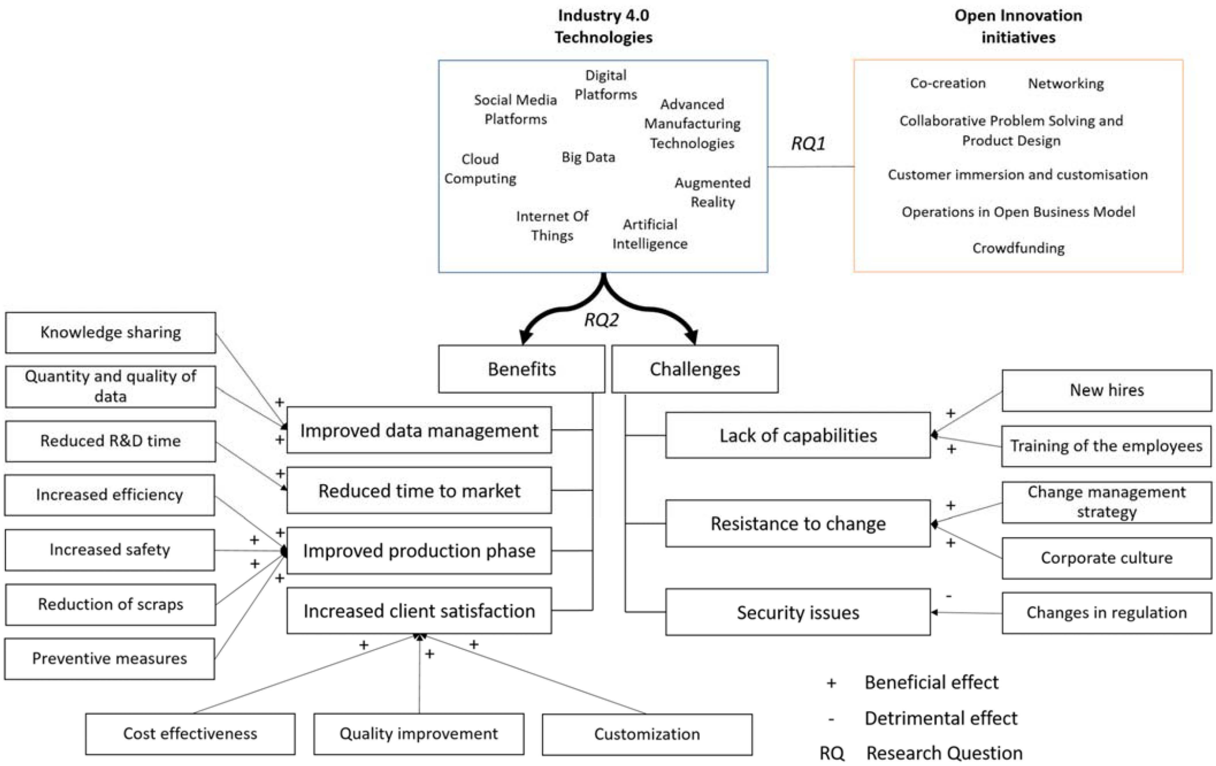

Fig. 3. I4.0 technologies enabling OI initiatives - benefits and challenges.

the stratified and modular nature of the digital economy allows new perspectives for openness. Digital platforms facilitate the relationship between entrepreneurial projects and possible crowdfunders. Indeed, entrepreneurs can promote their projects and use the visibility of the platform to reach potential investors. Furthermore, the literature points out that social networks play a relevant role in this context, favoring connections and communications among users and promoting dissemination worldwide [72], [103]. Of note, the interviewees also provided an example of the reverse link, i.e., crowdfunding as an enabler for the adoption of artificial intelligence.

5) Customer Immersion and Customization: Social media and digital platforms have a key role in favoring the initiatives of customer immersion and customization. Indeed, they facilitate the tracking of trends in consumer interests, comparing similar products, and designing an answer focused on addressing consumer interests. However, the link between smart devices and digital platforms contributes to data collection, but it can lead to security issues. Therefore, firms should equip themselves with cybersecurity technology to protect consumers' sensitive data. In contrast with the findings of this article, Ferràs et al. [104] conceptualized the reverse link, i.e., the substantial contribution of I4.0 technologies (Big Data and artificial intelligence in particular) in supporting customer immersion and customization by creating a more immersive experience. Moreover, Bonfanti et al. [31] stressed the importance of virtual reality for a personalized experience.

6) Operations in Open Business Model: It emerged a substantial contribution of I4.0 technologies for the operations in the Open Business Model. In particular, technologies that have a substantial influence are connectivity, Big Data, artificial intelligence, and cloud computing. Cloud computing and Big Data represent a tangible example of industrial connectivity technology: by lowering connection and data storage costs, for example, it is possible to use industrial applications to manage asset performance, take advantage of predictive maintenance services, and better control resource distribution. It is possible, for example, to develop a more transparent and faster interaction with external suppliers, allowing for lower inventory levels and less transportation activities. The role of artificial intelligence also emerged from the review of Strazzullo et al. [4], while Big Data and cloud computing are not mentioned.

B. RQ2: Which Factors Influence the Implementation of OI Enabling Technologies?

This section discusses the benefits and challenges of the identified I4.0 technologies, also providing insights about the factors that positively or negatively affect benefits and challenges. Fig. 3 summarizes the overall findings.

1) Benefits: The interviewees pointed out that I4.0 technologies improve the quantity and quality of data and facilitate data sharing among the actors involved in the innovation process. These factors contribute to the improvement of data management. For instance, the data collected by such technologies can enable companies to obtain detailed information about the quality of the components and conduct analyses on those that are the causes of production losses. Afterward, data can be classified and evaluated using other tools, including a series of reports tailored to the user. In several cases, each main actor in the supply chain can access the data and conduct deep analyses, ultimately helping the firm in improving production KPIs. These findings are in line with previous studies examining I4.0 technologies in general, such as [105], [106], and [107]. The reduction of the time to market is also seen as a relevant benefit by the interviewees, which is often determined by a reduction of the R&D time. In particular, I4.0 technologies improve and speed up the relationship with the client by, for example, allowing multiple feedback in a shorter time about a prototype. An interviewee reported a reduction of the R&D time from 14–18 months to 6–7 months.

The improvement of the production phase is also a key benefit of the identified I4.0 technologies. The main elements determining such an improvement are increased efficiency, increased safety, reduction of scraps, and preventive measures. Regarding the increase in efficiency, this driver is also stressed by Horváthová et al. [108], who point out the role of I4.0 technologies in increasing the efficiency of leather cutting in the automotive industry. As summarized by Robla-Gomez et al. [109], a relevant stream of literature focuses on the safety aspects of human–robot collaboration, presenting several related challenges (e.g., injuries due to collision). However, various procedures are now available to deal with this issue.

Of note, the findings of this article highlight increased safety due to the introduction of I4.0 technologies. Moreover, I4.0 technologies give the opportunity to preventively deal with potential issues (e.g., breakage of production systems), thereby improving the production phase. Another relevant benefit determined by such technologies is an increase in client satisfaction. Three factors substantially contribute to this increase: cost effectiveness, quality improvement, and customization.

2) Challenges: The challenges that emerged from the interviews can be categorized into three main domains: lack of capabilities, resistance to change, and security issues.

Regarding the first, companies are still in the early stages and need to learn how to integrate digital technologies into their processes. The lack of capability is also often discussed in the literature as one of the main challenges for the development and deployment of I4.0 technologies [110], [111], [112]; therefore, these findings confirm such a stream of literature. Shamim et al. [113] focused on the remedies, arguing that an appropriate management approach is essential to develop the capabilities needed for the implementation of I4.0 technologies.

Regarding the second domain (i.e., resistance to change), the introduction of I4.0 technologies is not different from other major changes; indeed, the employees are often not willing (at least as a general and first approach) to change their work routine. These findings are in line with the findings of Raj et al. [96] in the general case of I4.0 technologies and with the findings of Lee and Lee [114] in the specific case of the Internet of Things. Additionally, the interviewees suggested two main remedies to overcome such challenges, i.e., an appropriate change management strategy and corporate culture.

Regarding the third domain, security issues represent a relevant challenge for adopting I4.0 technologies. Indeed, a cyberattack in the I4.0 field can have a disastrous impact, compromising activities, leading to the deterioration of products, damage of systems and devices, downtime of production, and consequent financial and reputational losses. Security issues are also negatively influenced by frequent changes in regulations.

Fig. 3 summarizes the information presented and discussed in Sections IV and V, highlighting the I4.0 technologies that emerged as enablers of OI initiatives (i.e., RQ1), along with the factors (i.e., benefits and challenges) that influence the implementation of OI enabling technologies (i.e., RQ2). Additionally, by leveraging the information in the previous section, we included several elements that have a detrimental or beneficial effect on the challenges and benefits identified.

VI. Conclusion, Implications, and Future Research Opportunities

A. Conclusion

Policymakers, practitioners, and academics are increasingly discussing I4.0 technologies and OI initiatives. Both the deployment of I4.0 technologies and the opening up of the innovation process are essential for creating value-added for organizations and society. Remarkably, these two domains are often discussed separately both in the industrial and scientific literature. Most of the studies often propose only claims or conceptualizations about their link. This article addressed this gap in knowledge by empirically investigating the link between I4.0 technologies and OI initiatives. By leveraging interviews with practitioners (with experience in both OI initiatives and I4.0 technologies), this article addressed two RQs providing two main contributions. Regarding the first RQ, "Which Industry 4.0 technologies enable Open Innovation initiatives?", the authors identified specific I4.0 technologies that enable OI initiatives, as reported in Fig. 2. Moreover, the research led to identifying examples of the reverse link, i.e., OI as an enabler of I4.0.

Regarding the second RQ, "Which factors influence the implementation of Open Innovation enabling technologies?", the authors identified and examined four main benefits (i.e., improved data management, reduced time to market, improved production phase, and increased client satisfaction) and three main challenges (i.e., lack of capabilities, resistance to change, and security issues). The authors presented a graphical representation of the empirical findings in Fig. 3, highlighting the factors influencing benefits and challenges. The findings are also discussed through the lens of the existing literature in Section V. According to the authors, such benefits could be increased, and the challenges could be reduced or overcome by leveraging OI initiatives. For instance, if collaboration initiatives are arranged with an I4.0 experienced partner, the production phase could be further improved by leveraging such an experience and, at the same time, reducing the challenge related to the lack of capabilities. OI can provide relevant advantages in the context of I4.0, supporting companies in implementing digital solutions. OI can reduce risks in innovation projects for the adoption of advanced processes, reduce R&D costs, accelerate the adoption

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of new technological trends, better interact with the innovation ecosystem, and identify new opportunities for business and growth in the context of I4.0.

B. Practical Implications

This article has at least two main practical implications.

First, it identifies the benefits and challenges that arise from the use of digital technologies associated with OI practices. In particular, this article identifies and examines the following four benefits:

1) improved data management;
2) reduced time to market;
3) improved production phase;
4) increased customer satisfaction.

Furthermore, this article identifies and examines three challenges: 1) lack of capabilities, 2) resistance to change, and 3) security issues. These benefits and challenges are relevant for managers in the evaluation process leading to the decision to adopt or not a combined use of technologies and OI practices.

Second, the several combinations of I4.0 and OI practices identified, along with the benefits identified and examined through the thematic analysis, can serve as a strategy for companies. For instance, managers aiming to increase customer satisfaction can adopt cocreation practices enhanced by augmented reality and advanced manufacturing. Additionally, companies interested in adopting robotics could be supported by cocreation solutions to improve the performance of the technology. The benefits determined by the interplay of cocreation, advanced manufacturing, and virtual reality are also presented in other sectors, such as tourism and healthcare [115], [116]. Additionally, in the automotive sector, there are several applications of augmented reality for cocreation. Renault developed the virtual showroom "Virtual Studio," where customers can view their virtual vehicles from anywhere in the world and cocreate their own models. Furthermore, practitioners could leverage the link between collaborative problem-solving and product design and IoT, connectivity and advanced manufacturing to improve production processes. Indeed, the analysis shows how the manufacturing phase can benefit from the use of this combination of I4.0 technologies–OI practices. A study by Deloitte is in line with this result; indeed, it shows that, by introducing IoT, smart objects can be designed in the product design phase, creating an effective networked system [117]. Nike provides an example of the integrated application of collaborative design and IoT; the company launched a new pair of trainers that adapt to the shape of the wearer through remote control via smartphone. By leveraging the IoT, wearers can modify the setting of the shows according to their preferences.

C. Contribution to the Body of Knowledge

This study enriches the body of knowledge at the intersection between the OI domain and the I4.0 domain. For instance, this article shows, among others, how companies can benefit from investing in I4.0 technologies in their OI strategies. One of the most important contributions for academics is that the discussion not only stays at the potential level but goes a step further by empirically examining the relationship between the OI domain and the I4.0 domain, leveraging first-hand experience from industry experts. Furthermore, Fig. 3 can be a valid reference model for analyzing the collaborative use of I4.0 technologies from an OI perspective.

D. Limitations and Future Research Opportunities

This study presents one main limitation. The list of "I4.0 technology–OI initiative" links has been derived from a limited number of interviewees. However, it represents an exploratory attempt to define specific testable links. The next logical step is to test such links involving a significant number of participants. The findings of this article are a trigger for future exciting research about OI initiatives and I4.0 technologies. According to the authors, the following are particularly relevant areas for future research.

1) Examining the relationship between I4.0 and OI in specific subsectors (e.g., automotive, construction).
2) Quantitatively investigating the economic merit of the link (and of specific links) between I4.0 technologies and OI initiatives.
3) Examining how OI initiatives can influence the benefits and challenges of the identified I4.0 technologies.
4) Investigating the reverse link, i.e., how OI activities can support the adoption of I4.0 technologies.

Appendix

TABLE IV
DETAILS ABOUT THE INTERVIEWEES

Company	Role of the informants	Date	Industrial sector
Company 1	Innovation Manager	01/04/21	Information and Communication Technology
Company 2	Chief Digital Officer and Chief Executive Officer	03/05/21	Machinery
Company 3	Chief Information Officer	07/04/21	Trade
Company 4	Executive Vice President Digi&Met	20/04/21	Other manufacturing activities
Company 5	Chief Information Officer	07/04/21	Electronics
Company 6	Chief Information Officer	16/04/21	Machinery
Company 7	Group Industrial Director	20/04/21	Metallurgy
Company 8	Operations Manager	21/05/21	Machinery
Company 9	Managing Director	12/05/21	Food and Beverage
Company 10	Chief Information Officer	23/04/21	Electronics
Company 11	Vice President	05/05/21	Machinery
Company 12	Business Development Executive	05/05/21	Transportation and Logistics
Company 13	R&D Manager	03/05/21	Metallurgy
Company 14	Chief Executive Officer	08/04/21	Paper and printers
Company 15	Head Of Digital Development	14/04/21	Rubber-plastic
Company 16	General Manager	17/06/21	Machinery

TABLE V
SEMISTRUCTURED QUESTIONNAIRE QUESTIONS LAYOUT ADAPTED FROM [118]

Semi-structured questionnaire questions	Purpose
1) Does your company adopt OI initiatives?	Preliminary questions
2) In your company, in which areas do you use I4.0 technologies?	
3) Which of the following OI initiatives your company has adopted? (list of the initiatives[1])	RQ 1: Which I4.0 technologies enable OI initiatives?
4) Which of the following I4.0 technologies your company has implemented? (list of the technologies[2])	
5) According to your experience, which of these technologies support OI initiatives?	
6) What are the benefits of implementing such technologies?	RQ 2: Which factors influence the implementation of OI enabling technologies?
7) What are the challenges of implementing such technologies?	

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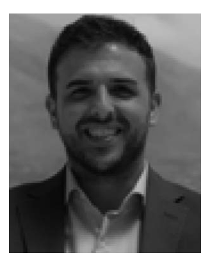

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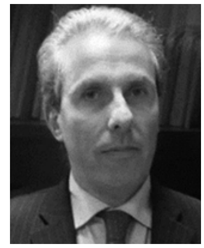

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