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Full, hybrid and platform complementarity: Exploring the industry 4.0 technology-performance link

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ABSTRACT

Literature has increasingly recognized that manufacturing companies should implement a synergic bundle of solutions to fully exploit the potential of Industry 4.0 (I4.0), rather than opting for a scattered technological adoption. Enabling I4.0 technologies, such as cloud computing, artificial intelligence, and additive manufacturing, can be implemented through various combinations to achieve different impacts on a company's performance. But what are the possible ways of combining I4.0 technologies into bundles, and do these ways actually help to achieve a performance that outperforms the adoption of single technologies?

This study aims to identify the potential patterns of the technological complementary of I4.0 by considering enabled applications and performance outcomes. We interviewed 13 Italian experts in the I4.0 field, and then combined the obtained information with secondary data collected from more than 150 I4.0 use cases, as well as from websites, reports and press releases. By adopting a systems theory lens, the results of the analysis have allowed us to identify the specific performance effects of both scattered and joint technological adoptions in different application areas. Interestingly, specific examples of I4.0 complementarities emerged, namely full, hybrid and platform complementarity.

This study contributes to the growing research on I4.0 outcomes by extending the concept of technological complementary within the I4.0 context. Results show that bundles of technologies have a broader effect on performance than when the same technologies are adopted in isolation, but also that single technologies can impact specific applications and the overall performance of a firm via a systematic I4.0 transformation path.

1. Introduction

The digital transformation of businesses, products and processes from the Industry 4.0 (hereafter I4.0) perspective, which entails both disruptive changes and far-reaching opportunities (Galati and Bigliardi, 2019), is increasingly pervasive among firms. In order to obtain a better understanding of the phenomenon, many scholars (e.g., Dalenogare et al., 2018; Tortorella and Fettermann, 2018; Frank et al., 2019; Büchi et al., 2020) have investigated the key features, adoption, and impact of the core I4.0 technologies, such as the Internet of Things (IoT), Cloud computing, Big Data and Analytics, and have highlighted a strong interdependence and interconnectedness among them. Most I4.0 technologies have their own unique capabilities of improving operations, and many technologies - such as Additive Manufacturing - have been experiencing exponential development in the last few years (Wang et al., 2019).

The range of potential benefits and impacts of I4.0 on manufacturing operations has been demonstrated by the different uses and adoption patterns of its enabling technologies (Frank et al., 2019). Literature has increasingly recognized that manufacturing companies should implement a synergic bundle of solutions to fully exploit the potential of I4.0 technologies (Tortorella and Fettermann, 2018; Klingenberg et al., 2019; Enrique et al., 2022b). Integrating I4.0 solutions and practices is also shown to improve resilience and, thus, responsiveness to achieve performance stability, mitigating the negative disruptive effects (e.g., of the Covid-19 pandemic) on companies' operational and financial performance (Bianco et al., 2023). In this sense, technology adopters should aim for a digital transition that entails adopting smart business solutions

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deriving from a complex system of interrelated technologies (Benitez et al., 2020), rather than a disconnected purchase of technologies from different providers (Benitez et al., 2022). However, less is known about potential I4.0 complementarities and related performance effects. Specifically, the concept of complementarity implies that adding a technology, when another technology has already been adopted, has an incremental effect on performance than adopting the same technology in isolation (Milgrom and Roberts, 1990).

The current literature has explored the conditions that favor the adoption process of I4.0 technologies, but has overlooked the different ways I4.0 technologies can be combined into bundles according to their functionalities, as well as whether the adoption of bundles can outperform the adoption of single technologies. On the one hand, the outcomes of specific technologies should be considered, as firms may implement them in isolation (Gillani et al., 2020). Some contributions have started to differentiate and combine I4.0 technologies into levels or bundles (e.g., Hahn, 2020; Luz Tortorella et al., 2021), but overlooking how their joint adoption could make the most in relationship with benefits for firms instead of a stand-alone implementation. The effect of these technologies on performance, especially at a firm level, is still a concern for practitioners (Frank et al., 2019). On the other hand, I4.0 technologies can be implemented in various combinations, thereby achieving different positive impacts on the performance of companies (Büchi et al., 2020). Recently, scholars performed quantitative studies (e.g., Dalenogare et al., 2018; Enrique et al., 2022b) to identify possible groups of technologies and the effects of these single groups on performance or specific manufacturing objectives. However, further research is needed to understand how combinations of I4.0 technologies – and their functionalities – can be realized in multiple ways, aiming to better unleash performance outcomes beyond single technology adoption. By carrying out such research, the synergic effects reached thanks to various integrations between technologies and related functionalities could be systematically identified, and the different emerging bundles-performance links mapped, beyond the strict inclusion of one technology – or one functionality – into a single bundle. This would increase managers' awareness to invest in certain bundles of I4.0 technologies, and ways to achieve complementarity, by considering their potential to generate added value for both their business and customers, while limiting related management complexity (Klingenberg et al., 2019; Ricci et al., 2021). Thus, different combinations of I4.0 technologies and applications should be explored with their expected performance outcomes (Culot et al., 2020), and also to substantiate the concept of I4.0 through the identification of the benefits and cost advantages, in terms of revenue potentials and required investments (Hofmann and Rüsch, 2017). In other words, despite the vast emerging literature on I4.0, we have limited cues on the following research question: "*What are the complementarities arising between I4.0 technologies, considered the impact of their joint adoption on different performance dimensions?*"

To provide a first answer to this research question, this study aims to identify the potential patterns of the technological complementary of I4.0 while considering enabled applications and performance outcomes. We aim to further extend the current literature on the joint adoption of I4.0 technologies by companies that should consider that some of them need to interact with others to fully deliver their functionalities, in relationship with expected benefits. In doing this, we employ a systems theory lens, which suggests that complex entities, such as I4.0, should be analyzed at the systems level through a holistic approach (e.g., Lawrence and Lorsch, 1967; Rousseau, 2015). Systems theory is particularly suitable to investigate this issue as the I4.0 paradigm is considered a complex system of interconnected technologies and subsystems which requires a high integration of competences at multiple levels (Benitez et al., 2020). Moreover, technological complementarity influences the value creation of business processes, their relationships at the operational and corporate level (Grant et al., 1994; Dalenogare et al., 2018; Luz Tortorella et al., 2021). Thus, the holistic perspective of the systems theory supports a more integrative and comprehensive understanding of I4.0 transformation outcomes (Imran et al., 2021; Luz Tortorella et al., 2021).

To reach this goal, we interviewed 13 Italian experts in the I4.0 field and addressed such topics as I4.0 technologies, I4.0 application areas, possible complementarities between I4.0 technologies, and the related performance effects. We also combined this information with secondary data collected from more than 150 use cases, and from other archival data. The results of the analysis allowed us to identify the specific performance effects of both scattered and joint technological adoptions. Moreover, we distinguished specific examples of I4.0 complementarities, namely full, hybrid and platform complementarity, and the role of I4.0 technologies in enabling such complementarities.

This research provides several contributions to both academics and practitioners. From a theoretical viewpoint, it identifies different combinations of I4.0 technologies and provides further nuance to the adoption patterns implemented by firms, thus answering to direct calls of previous literature for further research on the complementarity between I4.0 technologies (e.g., Culot et al., 2020). Furthermore, it also sheds light on the performance effects of both scattered and combined adoption of these technologies, a topic still highly debated in the literature (Szász et al., 2020). From a practical viewpoint, it supports managers in addressing their investments in Industry 4.0 by identifying the most versatile bundles and distinguishing several types of complementarities (full, hybrid and platform).

The paper is structured as follows. We provide an overview of the literature on I4.0 technologies, their bundles and their effect on performance in Section 2, also introducing the perspective of the system theory lens. We then describe the research methodology (Section 3) and the emerging results (Section 4). Finally, we thoroughly analyze and discuss our findings in Section 5 and conclude the paper with some final considerations on contributions and limitations.

2. Theoretical background

2.1. *A systems theory perspective to investigate performance effects in the industry 4.0 context*

Systems theory has been adopted as a framework to underpin the investigation of phenomena through a holistic approach, thereby encompassing a wide range of disciplines (Capra, 1997; Rousseau, 2015). The application of the systemic perspective to management and business fields leads to a vision of organizations as systems that need to be studied from a global viewpoint in order to underline their functioning and the relationships between their subsystems (e.g., the business processes), as well as between the organizations and their surrounding environment (Lawrence and Lorsch, 1967; Mele et al., 2010). Adopting these theoretical lenses acknowledges the high degree of integration in the factors that contribute to the value creation process (Grant et al., 1994), related to the individual business processes, but also to the technical and relational aspects (Mele et al., 2010).

In this sense, the adoption of the systems theory is particularly suitable for investigating the I4.0 transformation for at least two reasons: (1) a complex system of interconnected technologies and subsystems requires a high integration of competences, and (2) technological complementarity influences the value creation of business processes, their relationships and thus the overall firm (Grant et al., 1994; Dalenogare et al., 2018; Luz Tortorella et al., 2021). The application of I4.0 technologies is indeed expected to lead to significant performance improvements of the subsystems – i.e., the business processes – and of the overall company, by enabling a holistic approach (Fatorachian and Kazemi, 2021). To this aim, advanced digital technologies need to be aligned and jointly optimized by companies to effectively capitalize on the I4.0 transformation initiatives in order to achieve major business improvements (Imran et al., 2021).

This study adopts the systems theory to analyze the possible synergies between I4.0 technologies and their impact on performance outcomes at distinct levels. In general, I4.0 technologies are identified as components of supra-systems, i.e., the I4.0 applications and the entailed performance, while exploring their complementarity aims at capturing any possible interdependencies and patterns that allow the performance to be increased. In doing so, we consider the firm as the boundary of such supra-systems.

In the following paragraphs, we first develop a classification of I4.0 technologies tailored to the complementarity exploration and -then- provide an overview of the literature dealing with their possible combinations in wider systems. Finally, we offer a conceptual discussion of I4.0 applications and entailed performance, considering both scattered and complementary adoption of these technologies.

2.2. Classifications of industry 4.0 technologies

The use of I4.0 technologies represents a paradigm shift in manufacturing systems and industries that become smart and autonomous thanks to the application of advanced digital, information and communication, and operations technologies (Liao et al., 2017; Wang et al., 2019). By definition, I4.0 entails a wide variety of enabling technologies, design principles and management systems that can bring about several potential benefits, especially if they are interrelated and exploited in integration (Tortorella and Fettermann, 2018; Frank et al., 2019). Several authors, in an attempt to address the ‘technological profile of Industry 4.0’ (Ghobakhloo et al., 2021), have proposed different classifications and groupings of I4.0 technologies using different criteria and high heterogeneity of perspectives (Chiarello et al., 2018). In this paper, we organize the technologies by integrating three main factors that have been considered in previous classifications: network connectivity (local vs global) and technological elements (hardware vs software), as in Culot et al. (2020), and performed functionality as in Klingenberg et al. (2019). Thus, the resulting classification considers the managerial objectives, or the operational functionalities, which are enhanced by a technology to reach such objectives/functionalities in a ‘smarter way’, and which enable ‘specific intelligence’, according to the extent of connectivity and type of technological elements. Table 1 offers an overview of this classification by systematizing the technologies considered in the classifications and conceptual frameworks in literature (references are ordered temporally). I4.0 enabling technologies are thus identified as *Visualization technologies*, *Computing technologies*, *Network and sharing technologies*, *Digital production process technologies*, *Data processing technologies*, and below discussed.

Specifically, *Visualization technologies* extend the sensory perception of humans through access to virtual environments in order to generate and visualize operations, customer-related data and different multimedia information (Büchi et al., 2020; Kadir and Broberg, 2020). Such technologies include wearable technologies that connect the physical world with the virtual world, which are characterized by a high share of hardware components, such as smart glasses (Calabrese et al., 2020; Culot et al., 2020). *Computing technologies* allow a single object’s past and current behavior of to be simulated, represented, and modeled as a production process, up to the entire factory system (Ghobakloo, 2018; Calabrese et al., 2020). Such technologies include simulation and modeling solutions that allow the physical world to be reproduced in virtual models, where the physical model can be tested and optimized in the implemented model (Dalenogare et al., 2018; Büchi et al., 2020). The *Network and sharing technologies* class includes different solutions that enable resource sharing, online communication and network access to stored data, together with the technologies required to secure the data stored and exchanged, such as cybersecurity (Calabrese et al., 2020). They provide online functionalities, as is the case of cloud computing (and manufacturing), thus allowing common (on-demand) access to data, thanks to a network of highly distributed resources throughout the manufacturing system and even over the overall value chain (de Sousa Jabbour et al., 2018; Xu et al., 2018). *Digital production process technologies* include a set of solutions integrated with machinery and production lines to make the manufacturing and product processing operations more automated, safe and intelligent, thus enabling such a paradigm as flexible manufacturing system (Xu et al., 2018). For example, additive manufacturing technologies allow the flexible and connected prototyping of parts and products with complex functionalities, thereby facilitating customization and eliminating the need to assemble the material, but also to produce complex mechanical parts and tools that cannot be fabricated by regular processes (Bibby and Dehe, 2018; de Sousa Jabbour et al., 2018). Finally, the *Data processing technologies* categorization includes technologies that have frequently been considered at the core of the I4.0 paradigm, which are characterized by high data flow rates and demanding processing requirements (Xu et al., 2018), namely Artificial Intelligence and Big Data and Analytics. Such technologies allow large quantities of data to be processed and analyzed to enrich business knowledge and provide information-driven inputs for control and decision-making purposes (Moeuf et al., 2018; Calabrese et al., 2020; Culot et al., 2020). For example, combining intelligent sensors with Artificial Intelligence aims to optimize manufacturing in real time (Xu et al., 2018).

2.3. Combinations and bundles of I4.0 enabling technologies

Once recognized what I4.0 technologies can do in a ‘smarter way’ to reach operational functionalities and by enabling ‘specific intelligence’, managers could evaluate to apply them on a stand-alone basis. However, literature has increasingly recognized that a combination of I4.0 technologies is necessary for manufacturing companies to fully exploit their potentialities and deliver major impacts on business (Tortorella and Fettermann, 2018; Klingenberg et al., 2019; Enrique et al., 2022a). The isolated initiative of implementing a single I4.0 technology does not necessarily lead to positive impacts, as the most tangible benefits come from the synergy associated with their combined use (Porter and Heppelmann, 2014; Frank et al., 2019; Büchi et al., 2020). For example, Büchi et al. (2020) show that both the breadth of implementation of Industry 4.0 technologies and the pervasiveness of their use have a synergic impact on opportunity creation. More recent contributions differentiate and combine I4.0 technologies into levels or bundles.

Some authors identify technological bundles based on their application areas. Frank et al. (2019) separate the technologies into layers according to their main objective, namely, front-end technologies that accomplish operational and market needs with end-application purposes, such as Artificial Intelligence for predictive maintenance supporting smart manufacturing, and base technologies that involve connectivity and intelligence to enable front-end technologies, such as big data and analytics. They highlight that a growing maturity in I4.0 calls for the progressive adding of technologies into aggregated solutions, and some technologies support other ones, along specific adoption patterns. The literature review by Zheng et al. (2021) cites some important examples of combinations of digital and manufacturing technologies that are singularly proposed in previous research. The review focuses on the single technologies and their combinations in terms of specific applications in manufacturing business processes, such as IoT and cloud for production scheduling and control, or for customer relationship management. Hahn (2020) defines three bundles of digital technologies as enabling the three constitutive elements of socio-technical systems - specifically smart people, smart things and smart organizations - and considers all their possible combinations into further seven bundles. Their study in the business processes of 83 supply chain use cases reveals that smart things and smart organization technologies, as well as solutions that integrate these two technologies, are the most adopted, while companies still omit smart people technologies. Through a survey of 92 manufacturers, Enrique et al. (2022b) establish the definition of technological arrangements based on the production targets pursued by companies. In their study, the technology

Table 1
Enabling technologies of Industry 4.0: definitions and classification.

Industry 4.0 enabling technologies	Definition	References
Visualization technologies		
Augmented Reality, Virtual Reality, Mixed Reality	A series of devices that enrich (or lessen) the sensory perception of humans through access to virtual environments. In AR, this is accompanied by sensory elements, such as sound, smell, or touch. These elements can be added to mobile devices (smartphones, tablets, or PCs) or other sensors to augment vision (augmented-reality glasses), sound (earphones), or touch (gloves) in order to provide multimedia information.	Rüßmann et al. (2015), Liao et al. (2017), Chiarello et al. (2018), Ghobakhloo (2018), Frank et al. (2019), Klingenberg et al. (2019), Büchi et al. (2020), Calabrese et al. (2020), Culot et al. (2020), Ghobakhloo et al. (2021), Zheng et al. (2021).
Computing technologies		
Simulation and modelling (including digital twin)	Technologies required to reproduce the physical world in virtual models and allow operators to test and optimize the settings to obtain materials, productive processes (discrete elements), and products (finished or distinct elements), where synthesized virtual models simulate the properties of the implemented model.	Rüßmann et al. (2015), Liao et al. (2017), Ghobakhloo (2018), Frank et al. (2019), Klingenberg et al. (2019), Büchi et al. (2020), Calabrese et al. (2020), Culot et al. (2020), Ghobakhloo et al. (2021), Zheng et al. (2021).
Network and sharing technologies		
Cloud computing and cloud manufacturing	Web-based application whose information is stored on external servers, to facilitate the archiving and processing of massive quantities of data. It includes cloud services for products. Cloud manufacturing is specifically related to the I4.0 concept, and it refers to a virtual network/central platform which allows common (on-demand) access to data from all over the e-value chain to enable flexibility and efficiency gains.	Rüßmann et al. (2015), Liao et al. (2017), Bibby and Dehe (2018), Chiarello et al. (2018), Ghobakhloo (2018), Xu et al. (2018), Frank et al. (2019), Klingenberg et al. (2019), Büchi et al. (2020), Calabrese et al. (2020), Culot et al. (2020), Ghobakhloo et al. (2021), Zheng et al. (2021).
Cybersecurity	Technologies and security measures required to protect and secure the data stored and exchanged by devices connected to a computer network (e.g., interconnected corporate systems), as well as the user connected to the network and their assets.	Rüßmann et al. (2015), Ghobakhloo (2018), Klingenberg et al. (2019), Büchi et al. (2020), Calabrese et al. (2020), Culot et al. (2020), Ghobakhloo et al. (2021).
Blockchain	Distributed ledger technology that constitutes the backbone of cryptocurrencies, such as Bitcoin and Ethereum. It allows countless smart devices to perform transparent, secure, fast and frictionless financial transactions that are fully autonomous and without any human intervention in the IoT environment. The application of blockchain is not limited to financial services, and it can be used for any type of digitized transfer of information.	Chiarello et al. (2018), Ghobakhloo (2018), Xu et al. (2018), Klingenberg et al. (2019), Culot et al. (2020), Ghobakhloo et al. (2021), Zheng et al. (2021).
Internet of Things (IoT)	An information technology infrastructure characterized by the interconnection and integration of equipment, sensors and devices (things) through the Internet environment and wireless communication. The equipment provides information (such as the status, environment, production processes and maintenance schedule) to the network through embedded electronics and smart sensors (RFID tags, sensors, etc.), and it is also able to perform actions based on information from other devices.	Rüßmann et al. (2015), Liao et al. (2017), Bibby and Dehe (2018), Chiarello et al. (2018), Ghobakhloo (2018), Xu et al. (2018), Frank et al. (2019), Klingenberg et al. (2019), Büchi et al. (2020), Calabrese et al. (2020), Culot et al. (2020), Ghobakhloo et al. (2021), Zheng et al. (2021).
Digital production process technologies		
Additive manufacturing and 3D printing	Manufacturing technologies that transform 3D CAD models into physical objects. Digital models are printed, layer by layer, into one solid piece, in varied materials, such as metals, wax, plastics, resins and ceramics.	Rüßmann et al. (2015), Liao et al. (2017), Bibby and Dehe (2018), Chiarello et al. (2018), Ghobakhloo (2018), Frank et al. (2019), Klingenberg et al. (2019), Büchi et al. (2020), Calabrese et al. (2020), Culot et al. (2020), Ghobakhloo et al. (2021), Zheng et al. (2021).
Advanced robotics	Autonomous robots (e.g., Industrial Robots, Autonomous Guided Vehicles, or similar) designed to automatize highly repetitive operational or routinized processes. The advancements in robotics allow the systems to imitate the actions of humans, work autonomously, be consciously aware of the surroundings and adapt to unexpected scenarios.	Rüßmann et al. (2015), Bibby and Dehe (2018), Chiarello et al. (2018), Ghobakhloo (2018), Xu et al. (2018), Frank et al. (2019), Klingenberg et al. (2019), Büchi et al. (2020), Calabrese et al. (2020), Culot et al. (2020), Ghobakhloo et al. (2021), Zheng et al. (2021).
Collaborative robotics (cobots)	Robots that can interact with human operators and other robots in an intuitive self-learning way and without harming them.	Frank et al. (2019), Büchi et al. (2020), Calabrese et al. (2020), Zheng et al. (2021).
Energy management solutions	Tools used to determine where, when, and how energy resources are used, with the aim of eliminating or reducing waste. Energy management includes efficiency monitoring (relying on the data collection of energy consumption in electrical power grids) and improving it (achieved through intelligent systems for energy management that schedule intensive production stages in times with favorable electricity rates).	Frank et al. (2019), Büchi et al. (2020), Culot et al. (2020).
Data processing technologies		
Artificial Intelligence and Machine learning	Advanced tools that can analyze data gathered from sensors to monitor and forecast machinery failures, overloads or any other problems, and complement such systems as ERP in production planning through the creation of intelligent machines.	Liao et al. (2017), Chiarello et al. (2018), Xu et al. (2018), Frank et al. (2019), Klingenberg et al. (2019), Culot et al. (2020), Zheng et al. (2021).
Semantics/Semantic Web technologies	Tools that provide a common standard for communication and a standardized language for information exchange among different components, as standardized knowledge representation formalisms.	Liao et al. (2017), Chiarello et al. (2018), Ghobakhloo (2018), Klingenberg et al. (2019), Ghobakhloo et al. (2021).
Big data and analytics	Large amounts of data made available thanks to the acquisition of different sensors, which are gathered from systems and objects into a historical and real time dataset. They can be processed through analytics, which refer to the use of tools and statistical methods, data mining and machine learning, to process and analyze large quantities of data for application in managerial decisions and in an advanced predictive capacity.	Rüßmann et al. (2015), Liao et al. (2017), Bibby and Dehe (2018), Chiarello et al. (2018), Ghobakhloo (2018), Xu et al. (2018), Frank et al. (2019), Klingenberg et al. (2019), Büchi et al. (2020), Calabrese et al. (2020), Culot et al. (2020), Ghobakhloo et al. (2021), Zheng et al. (2021).

arrangements identify the technologies that should be implemented together to reach a specific production target, i.e., flexibility, process quality and productivity, distinguishing between general-purpose (supporting all targets), specific-purpose, and integrative-purpose (to enhance competing objectives) technology arrangements.

Overall, the general idea of combining the I4.0 technologies to exploit their potentialities has been widely discussed in the literature. However, a detailed overview of the potential patterns of such I4.0 complementarity still lacks.

2.4. Industry 4.0 applications and performance

Companies consider several factors that drive their decision to adopt I4.0 technologies (Ricci et al., 2021), and thus follow distinct strategies to improve performance outcomes (Kumar and Bhatia, 2021). Thus, it is pivotal to consider the different application areas and phases of technology adoption.

A definition of the synergic effects of I4.0 adoption should encompass the digitalization of – and the expected benefits from – products, equipment, intra-organizational operations and inter-organizational networks (Dalenogare et al., 2018; Ghobakhloo et al., 2021). To this extent, Frank et al. (2019) present four main applications, namely (1) smart manufacturing, which resorts to sensorized and automated production processes and systems (Fatorachian and Kazemi, 2018); (2) smart products, entailing the improvement of product capabilities by the integration of new services and digital technologies; (3) smart working, with technologies supporting workers' tasks, and (4) smart supply chain, creating a fully industrial networked environment with technologies extended across the supply chain (Ghobakhloo, 2018).

In this sense, the performance outcomes enabled by adopting I4.0 can be measured in terms of the extent of opportunities and benefits that are perceived or obtained in the various application areas (Büchi et al., 2020). There is substantial agreement among scholars about the positive impact of I4.0 adoption on a company's performance (Chauhan et al., 2021), with the main focus being on operational performance, flexibility and productivity gains (Gillani et al., 2020; Luz Tortorella et al., 2021; Nayernia et al., 2021). This positive impact firstly addresses the benefits of reducing operational costs, in part thanks to higher capacity utilization rates, and lower setup and maintenance costs (Kamble et al., 2020; Duman and Akdemir, 2021). Flexibility is also demonstrated to be enhanced into different dimensions and at different levels of the manufacturing plants (Enrique et al., 2022a). The time performance is generally reduced for both production processes, with fewer downtimes, reduced production, and delivery, and product development times, and thus a reduced launch time (Ghobakhloo et al., 2021). These performance improvements can also be extended to supply chain processes, thereby resulting in reduced lead times and minimization of the inventory and logistics costs (Bibby and Dehe 2018; Fatorachian and Kazemi, 2021). Furthermore, quality performance extends within and beyond the factory, with I4.0 enhancing both higher product quality and resulting in fewer production defects, which can be achieved on a continuous basis (Büchi et al., 2020; Kamble et al., 2020: Chauhan et al., 2021). In addition, some widely recognized benefits concern the product and service offering, with improved product customization and integration of new (digital) services (Dalenogare et al., 2018), thus resulting in higher customer satisfaction (Büchi et al., 2020). Indeed, I4.0 can contribute to the creation of better value propositions, through the introduction of the previously mentioned improvements of quality, flexibility, and delivery time (Szász et al., 2020). Apart from production, the implementation of I4.0 is increasingly being linked to human elements, with the increased importance of workers' safety and satisfaction, together with improved competencies, and sustainability gains (de Sousa Jabbour et al., 2018; Nayernia et al., 2021).

Table 2 summarizes the main benefits outlined in the recent studies that have investigated the impact of I4.0 technologies on performance.

Only the most recent contributions focus on company-wide performance impacts, and especially on financial goals. Kumar and Bhatia (2021) study the effects of I4.0 technologies on market performance, operationalized in terms of growth in return on sales, growth on sales and growth in market shares. Truant et al. (2021) investigate the effect of digitalization on the profitability performance of companies, including the return on investment (ROI) and the return on equity (ROE). Duman and Akdemir (2021) deal with the competitiveness of businesses, in terms of sales and profitability in organizational performance. However, all these studies adopt a survey methodology, without exploring the patterns of adoption that result in wider company performance outcomes.

Despite the number of contributions on the topic, studying the effects of I4.0 on performance outcomes is still considered an emerging area with a need for more empirical research beyond conceptual discussions (Kumar and Bhatia, 2021). The study of the technology-performance link should also expand from the increase in operational productivity, and the positive and immediate effects on performance, by considering possible trade-offs in their introduction (Bianco et al., 2023), e.g., in combining their functionalities and technological elements. This is particularly true for the combinations of bundles between I4.0 technologies, whose impacts have been considered only in few studies and using a broad perspective. Among these, the framework by Dalenogare et al. (2018) divides I4.0 technologies according to their expected contribution to performance, respectively Product Development technologies contributing to product performance, and Manufacturing technologies, bringing benefits for operational performance. While the product and operational benefits (together with side-effects including improvement in sustainability and reduction of labor claims) are discussed in relation to each technology, different potentialities of specific bundles are not investigated. Tortorella et al. (2019) combine I4.0 technologies that behave in an analogous way by identifying two bundles: process-related technologies, supporting the flow of materials and including sensors, remote monitoring and integrated engineering systems; and product/service-related technologies, supporting the flow of information and including rapid prototyping, virtual modelling and cloud services. They study their moderating role in the relationship between lean production and operational performance improvement, but they do not consider in the bundles some core solutions as Artificial Intelligence and Big Data and Analytics, calling for further studies to include more advanced I4.0 technologies. Gillani et al. (2020) point out that digital manufacturing technologies (including 3D printing, robotics, RFID) positively impact operational performance if their functioning is properly supported by the technological context of the production, information and communication technologies. Thus, the authors state there is a path dependency between technologies, and accordingly a cumulative effect in the impact on firm operational performance. Conversely, the study does not investigate the specific links arising from joint adoption of technologies. Enrique et al. (2022b) identify four specific technological arrangements – defined as Vertical Integration, Virtual Manufacturing, Advanced Manufacturing Processing Technologies, and Online Traceability – that group the I4.0 technologies according to the specific production targets pursued by companies, i.e. flexibility, process quality and productivity. While the viewpoint on the specific expected target allows managers to better adopt specific technologies, the multiple ways to combine the single technologies to further increase the production targets are not considered.

The aforementioned weaknesses in previous literature provide further motivation to identify the potential patterns of the technological complementary of I4.0 while considering multiple ways to enable applications and performance outcomes of companies. In particular, relying on the systems theory lens presented in section 2.1, we adopt an inductive approach that leads to the development of a conceptual framework pertaining to the link between I4.0 technologies and the performance of a firm, with the aim of answering the following question: *What are the complementarities arising between I4.0 technologies, considered the impact of their joint adoption on different performance dimensions?*

Table 2
Performance effects resulting from the adoption of Industry 4.0 technologies.

Performance	Examples from literature	References
Reduced times	Speed of serial prototypes Speed of product production and delivery Reduced new product launch times/ time-to-market Enhanced machine flexibility Reduced machine downtimes	Büchi et al. (2020); Duman and Akdemir (2021); Enrique et al. (2022a); Ghobakhloo et al. (2021); Gillani et al. (2020); Szász et al. (2020)
Reduced costs	Reduced set-up costs Reduced operational costs Reduced maintenance costs Reduced cost of quality and errors	Büchi et al. (2020); Ghobakhloo et al. (2021); Chauhan et al. (2021); Duman and Akdemir (2021)
Higher quality	Higher product quality Higher conformance quality Higher reliability	Büchi et al. (2020); Duman and Akdemir (2021); Ghobakhloo et al. (2021); Gillani et al. (2020); Szász et al. (2020)
Higher plant productivity	Production (product mix/volume) flexibility Process flexibility Production quality and reliability Overall Effectiveness of the Equipment	Büchi et al. (2020); Enrique et al. (2022a); Enrique et al. (2022b); Ghobakhloo et al. (2021); Nayernia et al. (2021); Szász et al. (2020)
New customer offering	Improved product customization Enhanced customer experience and satisfaction Data-driven products and services	Büchi et al. (2020); Dalenogare et al. (2018); Duman and Akdemir (2021); Ghobakhloo et al. (2021); Chauhan et al. (2021)
Enhanced working conditions	Improved work quality Improved workers' safety Efficiency in decision making Education and learning Enhanced labor flexibility	Dalenogare et al. (2018); Duman and Akdemir (2021); Enrique et al. (2022a); Nayernia et al. (2021)
Better environmental performances	Reduction in wastes and emissions Energy consumption efficiency Resource consumption efficiency	Duman and Akdemir (2021); Kumar and Bhatia (2021); Nayernia et al. (2021)

3. Method

Our research question aims at examining the multiple combinations of I4.0 technologies, as well as their performance impact, by identifying the possible complementarities between I4.0 technologies. To achieve this aim, we rely on a qualitative inductive method (Edmondson and McManus, 2007). The adoption of a qualitative inductive method is well suited for this context as it overcomes some of the limitations that quantitative methods could have. For instance, limited information about the context may constrain the understanding of the context in which bundles of technologies are implemented. Dealing with qualitative data gives us the possibility to overcome this issue, as well as to selectively identify the performance impact that the adoption of bundles brings.

3.1. Research context

We selected Italy as the research context to explore the complementarity between I4.0 technologies, applications and the performance of firms. This choice is linked to the vibrant institutional attention that both governments and industry stakeholders have paid to the I4.0 phenomenon (Büchi et al., 2020). Starting from 2016, Italy has strongly promoted the diffusion of I4.0 technologies among large firms and small and medium enterprises. In this vein, the Italian government has taken several policy actions to foster the adoption of I4.0 technologies (e.g., Piano Nazionale Industria 4.0). At the same time, a number of public institutions have been emerging to facilitate the integration of I4.0 technologies with the production processes and products of firms. Among these, some local institutions, named Digital Innovation Hubs (set up at the province level), have been pioneers in facilitating firms' adoption of I4.0 technologies (Crupi et al., 2020). Moreover, in recent years (i.e., from 2019 onward), the Italian government has promoted a new policy to support firms in testing the feasibility of I4.0 for their purposes. This policy has led establishing eight Competence Centers distributed throughout the Italian territory. Competence Centers are centers of excellence founded through public-private partnerships between the main actors of the innovation ecosystem (universities, research centers, government and industrial partners) to disseminate information, implement orientation, consulting and practical trainings, conduct experimental research and carry out innovative pilot projects to guide Italian companies in the I4.0 transformation and 4.0 technologies effective adoption (Ietto et al., 2022; Müller and Hopf, 2017). Based on the importance of adapting to local needs, each of these Competence Centers focuses on certain I4.0 technologies (e.g., additive manufacturing, cybersecurity) and on different industries (e.g., manufacturing, aerospace). In short, the large and vibrant I4.0 ecosystem currently being developed in Italy makes the country a suitable setting to investigate the relationships of complementarity between I4.0 technologies.

3.2. Data collection

As is typical in qualitative research (Yin, 2014), we collected data from multiple sources.

Semi-structured interviews. First, we carried out semi-structured interviews with I4.0 experts. As highlighted by Hannah and Eisenhardt (2018), experts represent a reliable source of knowledge, thanks to their expertise in a specific topic that is not limited to the boundary conditions of a specific context. Considering their key role in the Italian context, we decided to rely on experts selected from the eight Competence Centers set up in Italy. However, we were able to engage with only six of them, as two did not agree to participate in this study. Therefore, we complemented such data through interviews with other highly renowned experts in the field. These experts were identified by referring to both public press releases (e.g., some of them were often cited as experts by general-interest and specialized press) and through a snowball approach

Table 3
Profile of the interviewees.

Interviewee number	Role	Affiliation	Description of the organization
1	Senior Researcher	National Research Center	Leading frontier research projects aimed at the development and improvement of I4.0 technologies, with particular focus on bridging basic and applied research
2	Senior Researcher		
3	Senior Researcher		
4	Chief Executive Officer	Company Alpha (system integrator)	Supporting companies in integrating I4.0 technologies in their businesses (specialized in AI, Big Data Analytics, IoT, Cloud Computing)
5	Head of the Hub	Digital Innovation Hub A	Training, digital road mapping, digital assessment and networking, specialized in Advanced Manufacturing.
6	Director	Digital Innovation Hub B	Training, networking, digital assessment and technology brokering over the whole I4.0 technology landscape.
7	Innovation Manager		
8	Director	Competence Center A	Dissemination, training, and the development of pilot projects and co-development with firms of customized industrial solutions on Advanced Robotics and Digital Technologies.
9	Head of Innovation and R&D projects	Competence Center B	Dissemination, training, and the development of pilot projects and co-development with firms of customized industrial solutions over the whole I4.0 technology landscape.
10	Chairman	Competence Center C	Dissemination, training, and the development of pilot projects and co-development with firms of customized industrial solutions on Cybersecurity.
11	General Manager	Competence Center D	Dissemination, training, and the development of pilot projects and co-development with firms of customized industrial solutions on Big Data and Analytics, the Internet of Things and Cloud Computing.
12	Chief Executive Officer	Competence Center E	Dissemination, training, and the development of pilot projects and co-development with firms of customized industrial solutions on cybersecurity and I4.0 for safety.
13	Chairman	Competence Center F	Dissemination, training, and the development of pilot projects and co-development with firms of customized industrial solutions on additive manufacturing.

(Noy, 2008), which ended up when theoretical saturation was reached. Overall, we conducted semi-structured interviews with 13 Italian I4.0 experts, including six directors/general managers of the Italian I4.0 Competence Centers created by the Italian Government,[1] three researchers from a national research center specialized in developing projects on I4.0 technologies with companies,[2] three representatives (i.e., director, head and innovation manager) of two Digital Innovation Hubs, and one CEO of a system integrator company. Further details about the interviewees can be found in Table 3.

The interviews took place between January and May 2021. They were conducted by at least two researchers who relied on a research protocol with open-ended questions (see Appendix A), as suggested by Yin (2014). Each interview was recorded and transcribed verbatim. Following Miles and Huberman's prescriptions (1994), the transcriptions were supplemented with contact summary sheets in which the essential data and insightful quotations that could help future theorizing were reported. Overall, we collected qualitative material for more than 17 h.

As shown in the research protocol reported in Appendix A, the interviews were structured around four main themes: I4.0 technologies, the application of I4.0 technologies, complementarities between I4.0 technologies and the related performance effects.

Archival data. We further complemented the information gathered through semi-structured interviews with secondary data. In particular, we analyzed the use cases developed by the Competence Centers and which were published on their websites, other generalist archival data (e.g., websites, reports and press releases) and a white paper prepared by one of the Competence Centers. Specifically, the use cases refer to I4.0 pilot projects implemented in companies that were assisted by the Competence Center staff. We collected a total of 152 use cases (see Appendix B for the details) in the form of short reports describing them, with different levels of detail. Descriptions may include information such as the aim of the application project, the problem it addresses, the scope of application (areas and processes of the company involved), the I4.0 technologies adopted, the type of partners involved (e.g., technology providers beyond the Competence Center staff), the performance measured, and the improvements achieved. The research team then used these data for triangulation purposes and to deepen the analyses. Furthermore, such data were particularly useful to identify and link the performance effect associated with each (combination of) I4.0 technologies.

Table 4 reports the data inventory, as well as the intended audience for each type of material that was analyzed. It is worth highlighting that not all the examined archival data reported in the table was coded and used for the research purposes, since some of the related contents were not of interest for our goals. In particular, starting from the 152 use cases and the 50 pages of other archival data, we considered only cases/reports that concern either (1) the implementation of combinations of I4.0 technologies in manufacturing companies (with and without mentioning the performance effects) or (2) the adoption of single technologies in manufacturing companies with an explicit reference to the affected performance outcomes. Cases not satisfying these criteria were excluded from further analyses. Examples of exclusions are the following: applications in context different from manufacturing (e.g., agri-food, tourism, mobility), specific technologies not clearly stated in the reports, description of single technologies adoption without mentioning the affected performance outcomes.

3.3. Data analysis

In order to gain a broader understanding of the complementarity between I4.0 technologies, as well as of their implications on the performance of firms, we adopted an inductive approach (Edmondson and McManus, 2007). The inductive approach is a bottom-up methodology that, starting from observations, leads researchers to recognize specific patterns that favor the emergence of knowledge (Langley, 1999). Once knowledge has emerged, researchers abstract such knowledge by developing a theory that not only represents the phenomenon under scrutiny, but also generalizes the emerged results.

In our research, we supplemented the inductive method with the interpretative approach provided by the grounded theory (Glaser and Strauss, 1967), which allows researchers to move back and forth from observations to abstraction and to iteratively build and refine an

[1] Top managers of Competence Centers were chosen as informants given their high-level overview of the several projects developed within each competence center. Furthermore, they are people with an excellent career (e.g., long experience as innovation managers or technology consultants) and thus with a profound knowledge of both the manufacturing sector and digital processes.

[2] Such experts also operate as independent evaluators of Industry 4.0 projects for the European Union and the Italian Government.

Table 4
Data inventory.

Data Type	Quantity	Material collected	Original (intended) data audience	Insights in particular for
Interviews	13 on experts on the I4.0 domain	17 h approximately and 105 pages of transcription	This study	I4.0 technologies, bundles, and performance link
Archival data	152 use cases	87 pages	Competence Centers, Firms, Press	I4.0 technologies, bundles, and performance link
	A white paper from 1 Competence Center	32 pages	Firms, Competence Centers	I4.0 economic and financial performance
	Other archival data (e.g., websites, press releases, reports)	50 pages	Firms, Competence Centers	I4.0 technologies and bundles

emergent theory (Suddaby, 2006).

To do this, we engaged with the data through expert interviews and secondary data analysis. The aim of this second step was to identify the potential complementarities of I4.0 technologies, in terms of technological combinations, their application domains and their effects on performance. Each interview transcript and secondary datum was subjected to multiple coding cycles, with the aim of developing the summary framework of complementarities. Each round of coding was undertaken using the NVivo software. Firstly, we proceeded with a line-by-line in-vivo coding of the data related to the links between I4.0 technologies, their applications, and the potential outcomes of their use. We coded in order to highlight technology performance links. This first coding phase was developed in parallel by two researchers. Several collective check-coding sessions (Miles and Huberman, 1994) were then dedicated to ensuring the reliability of the coded text. We proceeded by reducing the codes obtained in the first coding round and running a second round using theoretical coding (Saldaña, 2021). In other words, we reduced the codes obtained in the first round, while highlighting the number of technologies involved in the technology-performance link, as well as the type of technologies shared between the constituents of the group. Finally, we synthetized the second-level codes in the overarching theoretical structures by resorting to the impact that I4.0 technologies may have (i.e., single impact vs joint impact). The results of this coding phase are reported in Fig. 1. Finally, the results were discussed by adopting the systems theory lens. Specifically, we used the system theory lens 1) to lay the foundation of a model of technological complementarity among Industry 4.0 technologies, encompassing multiple ways of combining them into greater but also wider performance to be potentially reached, and 2) to elaborate on the principle of wholeness in the formulation of propositions.

4. Results

The experts' interviews, as well as the use cases, allowed to collect information on the applications and performance impacts of implementing single technologies and of adopting bundles of technologies. We relied on previous literature to categorize the results. In particular, we considered the application areas mentioned in section 2.4, namely: (1) smart manufacturing, (2) smart products, (3) smart working, and (4) smart supply chain (see Frank et al., 2019). Furthermore, based on the collected information, we further distinguished smart manufacturing and smart working into their main constituents, namely: production process, management, control and maintenance for the former, activities and training for the latter. As regards the performance impacts, we instead distinguished them according to the categorization presented in Table 2.

Overall, our results show that I4.0 technologies can impact a firm's performance when adopted both as stand-alone technologies and as bundles. The following paragraphs present the results of our engagement with the data and highlight the link between technologies (and combinations of technologies), applications and performance.

4.1. *Unbundled technologies and single impact on performance*

The first result of the data analysis is that the adoption of some classes of technologies can exert a direct impact on firms' performance, even if they are not combined with other I4.0 technologies. We labeled such technologies 'unbundled', as they can influence a firm's performance in a context of scattered adoption. It emerged, from the analysis, that four out of five technology groups belong to the unbundled category, namely, Network and sharing technologies, Data processing technologies, Digital production process technologies and Visualization technologies. Instead, Computing technologies never emerged as an effective stand-alone adoption. Only seven different technologies were either discussed by the experts or adopted in the use cases as potentially effective stand-alone solutions. Fifteen dimensions of performance (e.g., time-to-market) were instead mentioned as possible outcomes of their scattered adoption. Overall, all the performance categories seem to be positively affected by the adoption of such technologies, except for better environmental performance, which was never mentioned in the analyzed data. The performance outcomes most frequently cited were production efficiency increase, error reduction, and customer service enhancement.

Table 5 reports a summary of the unbundled I4.0 technologies and the relative applications through which they exert an impact on the performance of firms.

As far as Network and sharing technologies are concerned, the experts cited several times the adoption of IoT to create smart products, which can enhance customer service and improve the perceived product quality.

Instead, as regards the Data processing group, two technologies were discussed as stand-alone effective, namely Big Data and Analytics, and Artificial Intelligence. Compared to the other groups, the range of applications of Data processing technologies is quite large, and so are the types of performance that can be improved. It, in fact, emerged from the data that Big Data and Analytics can be adopted to manage and control the manufacturing process, thereby increasing the Overall Equipment Efficiency (OEE), but also as a smart working application to reduce the efforts needed to execute different tasks, including forecasting and demand planning. Furthermore, they can be used to develop smart products and achieve a higher customer service level, as highlighted by a manager of a Digital Innovation Hub:

> *"Company Beta (a drilling company) started analyzing the outcomes of previous jobs through big data analytics. In particular, they used big data to understand when they had to change a drill bit, and how long it took to drill mud or granite. Now they are leaders in estimating jobs, and they can provide very precise estimations to their customers. This is how big data has transformed their strategy: they are no-longer a drilling company; they are leaders in making estimations on drilling!"*
>
> Digital Innovation Hub B – Innovation Manager

According to our informants, there are instead two applications of Artificial Intelligence. First, they can be used to reduce management

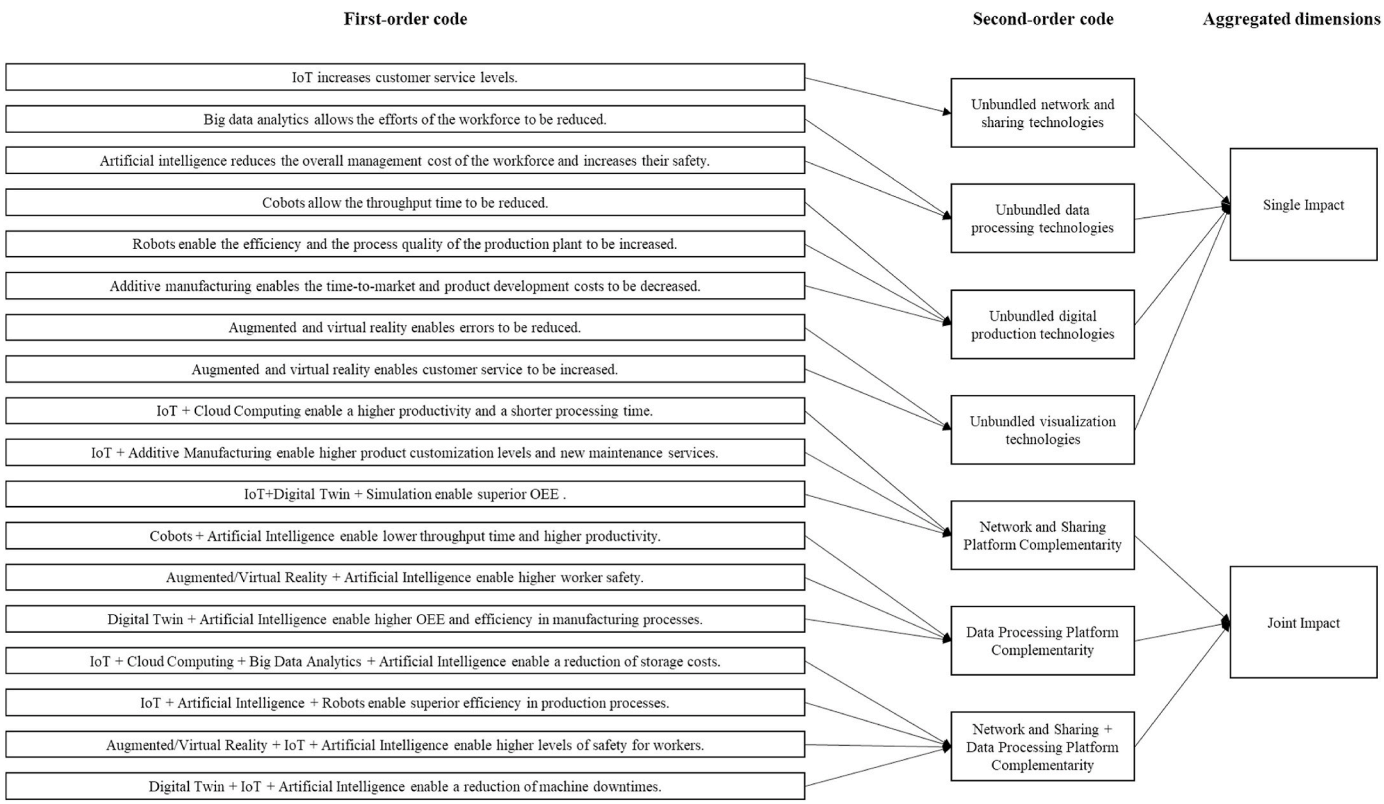

Fig. 1. Data structure
Note: For visual purposes, the data structure reports only some of the examples of the first-order codes, but reports all of the second-order dimensions, as well as all the theoretical structures. The full data structure, with the technology-application-performance link, can be desumed from the following Tables 4–6. The complete data structure (graphical version) is available from the authors upon request.

Table 5
Single technologies, applications and performance impacts.

Technology	Application	Performance	Impact
IoT	Smart product	New customer offering	Higher customer service level (2)
			Higher perceived quality (1)
Big data and Analytics	Smart manufacturing (management & control)	Higher plant productivity	Increased OEE (2)
	Smart product	New customer offering	Higher customer service level (1)
	Smart working (activities)	Enhanced working conditions	Reduced workers' efforts (2)
Artificial intelligence	Smart manufacturing (production process)	Reduced cost	Reduced quality control costs (2)
			Reduced cost of errors (1)
		Higher plant productivity	Increased production efficiency (1)
	Smart working (activities)	Reduced cost	Reduced quality management costs (1)
		Higher plant productivity	Increased work efficiency (1)
		Enhanced working conditions	Improved workers' safety (1)
Cobot	Smart manufacturing (production process)	Reduced time	Reduced throughput time (1)
	Smart working (activities)	Enhanced working conditions	Reduced workers' efforts (1)
Robot	Smart manufacturing (production process)	Reduced cost	Reduced cost of errors (1)
		Higher plant productivity	Improved production efficiency (1)
			Improved process quality (1)
	Smart working (activities)	Enhanced working conditions	Improved workers' ergonomics (1)
Additive manufacturing	Smart manufacturing (production process)	Reduced time	Reduced time-to-market (2)
		Reduced cost	Reduced product development cost (1)
Augmented/Virtual reality	Smart product	New customer offering	Higher customer service level (1)
			Improved maintenance service effectiveness (2)
	Smart working (activities)	Enhanced working conditions	Improved workers' safety (1)
	Smart working (training)	Reduced cost	Reduced cost of errors (1)
		Enhanced working conditions	Enhanced training speed (1)

Note: The numbers in parentheses indicate how many times the related performance was mentioned by the respondents and/or in use cases.

costs, improve efficiency, and minimize errors in the production process. This is particularly true for quality control processes, which are the subject of different projects developed by Competence Center A: here, photographic images of the products lying on a table or moving on a roller are analyzed by Artificial Intelligence algorithms to quickly identify possible defects and/or quality problems, and thus of expediting the quality control process. Second, these technologies can also be applied to support the workers' tasks and activities (i.e., smart working applications), as well as to improve process efficiency and enhance workplace safety.

Table 6
Bundles of I4.0 technologies.

Bundles		Examples
B1	Network and sharing + Network and sharing technologies (n = 5)	IoT + Cloud computing (n = 4) IoT + Cybersecurity (n = 1)
B2	Network and sharing + Data processing technologies (n = 36)	IoT + Artificial Intelligence (n = 9) Cloud computing + Artificial Intelligence (n = 4) IoT + Big Data and Analytics (n = 12) IoT + Cloud computing + Big Data and Analytics (n = 1) IoT + Cloud computing + Artificial Intelligence (n = 2) IoT + Cloud computing + Big Data and Analytics + Artificial Intelligence (n = 5) Cloud + Big Data and Analytics + Artificial Intelligence (n = 3)
B3	Digital production process + Network and sharing technologies (n = 11)	Additive manufacturing + IoT (n = 9) Robot + IoT (n = 1) Cobot + IoT + Cloud computing (n = 1)
B4	Digital production process + Data processing technologies (n = 23)	Cobot + Artificial Intelligence (n = 8) Robot + Artificial Intelligence (n = 15)
B5	Digital production process + Network and sharing + Data processing technologies (n = 4)	Robot + Cloud computing + Artificial Intelligence (n = 1) Robot + IoT + Artificial Intelligence (n = 2) Robot + IoT + Cloud computing + Big Data and Analytics (n = 1)
B6	Visualization + Data processing technologies (n = 8)	Augmented/Virtual Reality + Artificial Intelligence (n = 1) Augmented/Virtual Reality + Big Data and Analytics (n = 7)
B7	Visualization + Network and sharing + Data processing technologies (n = 3)	Augmented/Virtual Reality + IoT + Artificial Intelligence (n = 2) Augmented/Virtual Reality + Cloud computing + Big Data and Analytics (n = 1)
B8	Computing + Network and sharing technologies (n = 4)	Digital twin + IoT (n = 1) Simulation + IoT (n = 1) Digital twin + Simulation + IoT (n = 2)
B9	Computing + Data processing technologies (n = 4)	Digital twin + Artificial Intelligence (n = 2) Simulation + Artificial Intelligence (n = 1) Digital twin + Simulation + Artificial Intelligence (n = 1)
B10	Computing + Network and sharing + Data processing technologies (n = 4)	Digital twin + IoT + Artificial Intelligence (n = 2) Digital twin + IoT + Big Data and Analytics (n = 2)

Regarding production process technologies, our informants discussed the stand-alone applications of cobots, robots, and additive manufacturing. Cobots and robots can be used in the production process to improve the time and effectiveness of activities, as well as to relieve the workforce of heavy and non-ergonomic tasks. In this regard, one of the respondents remarked that:

> *"Cobots can certainly improve the operators' work: they not only speed up some processes, but they can also help the users in some critical activities, including data collection and/or heavy tasks. Why do we have to struggle to lift things when we can have something that lifts them for us?".*
>
> Competence Center A - Director

The advantage of additive manufacturing is instead linked to the possibility of improving the product development process, and of reducing the related time and costs thanks to the quick development of prototypes. Finally, augmented and virtual reality, two Visualization technologies, can be adopted for smart product and smart working applications. In the former case, they can improve the service offered to customers, and particularly the efficiency and effectiveness of maintenance activities, which can be guided remotely by the supplier, thanks to the reliance on augmented reality. In the latter case (i.e., smart working applications), they can improve the training speed, but also enhance the workers' safety and help reduce their potential mistakes. As the CEO of a Competence Center stated:

> *"Virtual reality and augmented reality can support the employees when maintenance activities are performed in fairly critical conditions: these technologies in fact allow a whole range of information to be constantly available and updated, so that the person in charge of the activities knows the conditions around him/her perfectly well and immediately understands what other interventions have been made or what potentially dangerous situations can occur. This increases the precision and safety of the related activities."*
>
> Competence Center E – CEO

4.2. Bundles of technologies: applications and performance impacts

The second result that has emerged from our engagement with the data shows that I4.0 technologies can also be combined in ten different bundles to increase firm performance (see Table 6).

Such bundles are underpinned by two main groups of technologies, which seem to play a pivotal role in all the other combinations, thus representing a starting point for their development: (1) Network and sharing technologies, and (2) Data processing technologies. They can indeed be combined not only with each other (B1, B2), but also with Digital production process technologies (B3– B5), Visualization technologies (B6 and B7) and Computing technologies (B8–B10).

Table 7 shows the results of the analysis on the relationship between bundles, applications, performance (our first-order categories in Fig. 1), and the relative impact.

The informants and the Competence Centers' use cases led to the identification of 33 performance dimensions (e.g., personnel cost reduction, OEE) that the ten bundles of I4.0 technologies can impact. The most frequently cited performance outcomes include error reduction, product quality increase, and increased worker safety.

The first bundle (B1), which combines different Network and sharing technologies (IoT and cloud computing), can be exploited to collect, convey, and store data. This enables a better monitoring of the production process, thereby allowing firms to improve not only their productivity, but also the efficiency of the maintenance activities. The following use case offers an effective example of this application:

> *"Problem faced: The company has available technologies and data but does not know how to collect, process and make them productive.*
>
> *Proposed technical solution: Infrastructure of sensors that allow continuous communication between all the elements that make up the production system. The solution includes a customized management software to share the value of the information collected: the data collected by each sensor is stored locally and then provided in the cloud, where the user has*

Table 7
Bundles, applications and performance impacts.

Bundle	Application	Performance	Impact
B1 *(Network and sharing + Network and sharing technologies)*	Smart manufacturing (production process)	Reduced time Higher plant productivity	Reduced processing time (1) Increased productivity (1)
	Smart manufacturing (maintenance)	Reduced cost Higher plant productivity	Reduced maintenance cost (1) Increased OEE (1)
	Smart working (activities)	Enhanced working conditions	Improved workers' safety (1)
B2 *(Network and sharing + Data processing technologies)*	Smart manufacturing (production process)	Reduced cost	Reduced production cost (1) Reduced cost of errors (2)
		Higher quality	Higher product quality (1)
		Higher plant productivity	Increased production efficiency (2) Increased production quality (1) Increased productivity (1) Increased reactivity (1) Increased production flexibility (1) Increased OEE (2)
	Smart manufacturing (management & control)	Reduced time	Reduced manufacturing downtimes (1) Increased on-time delivery (1)
		Reduced cost	Reduced transportation/storage cost (2) Reduced operational cost (2)
		Higher quality	Higher product quality (1)
		Higher plant productivity	Increased production flexibility (1) Increased OEE (1)
		Better environmental performance	Energy consumption efficiency (2)
	Smart manufacturing (maintenance)	Higher plant productivity	Increased OEE (4)
	Smart product	New customer offering	Customer service enhancement (2) Improved maintenance service effectiveness (2) Improved product customization (1)
	Smart working (activities)	Enhanced working conditions	Improved workers' safety (5)
B3 *(Digital production process + Network and sharing technologies)*	Smart manufacturing (production process)	Better environmental performance	Energy consumption efficiency (1)
	Smart product	New customer offering	Higher customer service level (2) Improved maintenance service effectiveness (4) Improved product customization (3)
	Smart working (activities)	Enhanced working conditions	Reduced workers' efforts (1)
B4 *(Digital production process + Data processing technologies)*	Smart manufacturing (production process)	Reduced time	Reduced processing time (3) Reduced throughput time (2)
		Reduced cost	Reduced cost of errors (1)
		Higher quality	Higher product quality (1)
		Higher plant productivity	Increased productivity (2) Increased production flexibility (1) Increased plant reconfigurability (1) Space optimization (1) Real-time monitoring (1)
		Better environmental performance	Energy consumption efficiency (2)
	Smart working (activities)	Enhanced working conditions	Improved workers' safety (4) Reduced workers' efforts (1) Improved workers' ergonomics (2) Improved life quality (1)
B5 *(Digital production process + Network and sharing + Data processing technologies)*	Smart manufacturing (production process)	Reduced time	Speed of production (1)
		Reduced cost	Reduced personnel cost (1) Reduced cost of errors (1)
		Higher plant productivity	Increased production efficiency (1)
B6 *(Visualization + Data processing technologies)*	Smart manufacturing (production process)	Reduced time	Reduced plant development time (1)
	Smart product	New customer offering	Improved maintenance service effectiveness (2)
	Smart working (activities)	Enhanced working conditions	Improved workers' safety (1)
	Smart working (training)	Reduced cost	Reduced cost of personnel training (2)
		Enhanced working conditions	Enhanced training speed (2)
B7 *(Visualization + Network and sharing + Data processing technologies)*	Smart product	New customer offering	Improved maintenance service effectiveness (1)
	Smart working (activities)	Reduced cost	Reduced personnel cost (1)
		Enhanced working conditions	Improved workers' safety (1)

(*continued on next page*)

Table 7 (*continued*)

Bundle	Application	Performance	Impact
B8 *(Computing + Network and sharing technologies)*	Smart manufacturing (production process)	Higher plant productivity	Increased production efficiency (2)
	Smart manufacturing (management & control)	Higher plant productivity	Increased OEE (1)
	Smart working (training)	Reduced cost	Reduced cost of errors (1)
B9 *(Computing + Data processing technologies)*	Smart manufacturing (production process)	Higher plant productivity	Increased production effectiveness (1)
	Smart manufacturing (management & control)	Higher plant productivity	Increased production efficiency (1) Increased OEE (1)
	Smart working (activities)	Enhanced working conditions	Improved workers' safety (1)
B10 *(Computing + Network and sharing + Data processing technologies)*	Smart manufacturing (production process)	Higher quality Higher plant productivity	Higher product quality (1) Increased production quality (1)
	Smart manufacturing (maintenance)	Reduced time Higher quality	Reduced machine downtimes (1) Higher product quality (1)

Note: The numbers in parentheses indicate how many times the related performance was mentioned by the respondents and/or in the use cases.

a dedicated profile. This makes it possible to execute a remote control of processes.

Numerical results: 20% productivity increase, 12% maintenance cost reduction, 18% order management time reduction."

Competence Center A – Use Case n.31

Furthermore, when combined with wearable devices, the B1 bundle also allows specific body-area networks to be created that can be used to monitor the workers' tasks from a safety viewpoint, as it happens in a project developed by Competence Center A with a manufacturing company:

"Problem addressed: reduce workplace accidents and ensure safety in production sites.

Proposed technical solution: The SmartSafety solution allows for continuous monitoring of personnel safety at work, ensuring compliance with all safety standards. Through the use of high-performance battery-powered wearable devices, linked to a wireless network and the IoT SmartPlatform, the indoor and outdoor sub-metric localization functions are provided, as well as the verification of the presence and correct use of slave devices through the creation of a specific body-area-network.

Results: less work accidents and operators' safety."

Competence Center A - Use Case n.34

The Network, sharing and data processing technology bundle (B2) is clearly the most frequently cited by our informants and the most recurrent among the use cases. The results show that, except for training tasks, B2 enables all the other I4.0 applications and, in particular, smart manufacturing (including all the sub-areas). First, this bundle allows a complete connection of the machines to be created, which helps them to understand each other and reciprocally adapt their work (i.e., production process sub-application). This capability, typically enabled by IoT, Big Data and Analytics, as well as by cloud computing and artificial intelligence, results in improved product quality, lower production costs and increased plant performance. Second, B2 can support the management and control of a production process, thanks to the collection, storage, and advanced analysis of manufacturing data, thus improving almost all the performance categories, including energy consumption. In this regard, Competence Center A recently supported a firm operating in the automotive sector to diagnose energy inefficiencies in its industrial process by leveraging IoT and big data and analytics. The solution has been installed into 4 plants of the automotive company, leading to a 5% energy saving (quantified as 40 million euros). The use case describes the application as follows:

"Despite the availability of IoT systems, which make it possible to relate energy consumption to the operating parameters of the plant, the large amount of available data often prevents them from being treated and analyzed through traditional methods. New analysis tools, which are capable of transforming data into useful information for decision-making, are needed.

The technical solution proposed for this problem is an intelligent system to diagnose energy inefficiencies in industrial production processes that consists of:

1. Gateway to / from MES systems.

2. Algorithms for descriptive data analysis, aimed at (1) extracting information concerning the relationship between energy consumption and production, and at (2) analyzing electricity consumption peaks and machine standby situations.

The proposed solution would allow the production process consumption to be understood and optimized, thus enabling a more efficient energy management, based on lower costs and equal production levels."

Competence Center A – Use Case n.20

Third, this bundle supports predictive maintenance and can potentially improve a company's OEE. Besides smart manufacturing, smart product and smart working applications can also be enabled by combining Network, sharing and data processing technologies. For instance, in a project developed by Competence Center D, a company collects information on how the customers use their products and, consequently, offers customized services, as described by the spokesperson:

"The use of sensors and IoT, and the introduction of an advanced analysis and real-time data collection model, allow us to provide an original and amplified experience to our customers, thanks to the personalization of services (including maintenance) through the data-driven management of the coffee machines."

Competence Center D – General Manager

The B3, B4 and B5 bundles emerged from the involvement of digital production technologies. The latter are combined in B3 with Network and sharing technologies, and particularly with IoT and cloud computing. The combination most frequently cited by our informants involves additive manufacturing and IoT, and it enables smart product applications while improving the service level offered to customers, in terms of both product personalization and maintenance support. According to our analyses, we found this element in both Competence Center B and Competence Center F. On this topic, the chairman of Competence Center F said:

"… We worked on the development of a 3D printed metal heat exchanger, designed to be modular and smart, for the aerospace, oil and gas industries and for several other industrial fields. Apart from representing an innovative solution for the absence of welds or joints, it has also been designed to be modular and equipped with connected sensors for predictive maintenance, in order to respond to the precise and still unsolved problem of reducing the maintenance times and costs of heat exchangers in critical applications."

Competence Center F - Chairman

The fourth bundle (B4), which combines robots and cobots with artificial intelligence, has two main applications. First, it can be used in a production process to reduce the times and improve the cost efficiency, quality, and management of a plant. Second, as a smart working application, it can enhance the workers' safety, but it can also substitute the workers themselves in the execution of tasks, thus relieving them of heavy tasks. Compared to the stand-alone applications of cobots and robots, their combination with artificial intelligence algorithms creates a more dynamic solution, which is able to change behavior according to the specific contextual conditions. An example is offered by one of the analyzed use cases, related to a multinational manufacturer of industrial components (especially for the automotive industry) willing to automatize the production process and eliminate non-value-adding activities, while maintaining a flexible design. Here, robots equipped with vision and artificial intelligence systems can measure functional and dimensional parameters and distinguish among different components to automatically operate a variety of specific manipulations and assemblies, increasing productivity and reducing the environmental impact. In both the B3 and B4 cases, the impacts on performance are much broader than those of the digital production technologies adopted in isolation.

The last bundle involving digital production technologies (B5) is a combination of the two previous groups. As shown in Table 7, the applications mainly concern the automatization of the production process, which introduces significant benefits, in terms of time reduction, cost efficiency and productivity.

The sixth (B6) and seventh (B7) bundles, which are based on Visualization technologies, are typically exploited to offer smart products or support the workers' activities and training. In this regard, our informants of Competence Centers B and D stated that:

"One of our partners developed a solution based on a wearable IoT device (i.e., smart glasses) that observes the environment where the operator acts from 'his/her point of view' and analyzes it. A mixed reality video camera and screen guide the operator around the objects that have to be used and the operations that have to be performed. Through Machine Learning algorithms that process the interactions between workers and objects and, according to the current scenario, the system is able to foresee the next movement of the operator and thus the object he/she will interact with. This allows situations of possible risk for the operator's safety to be prevented, thanks to the activation of alerting signals in augmented reality."

Competence Center B – Head of Innovation and R&D Projects

"For example, the big data collected from the production process can be explored by analytics to recreate, for each piece of machinery and each production line, the assets necessary to manage the maintenance, safety, training and troubleshooting processes in a smart and digital way, through the support of virtual reality. As a result, the workers' safety can be improved, while the times and costs of training can be reduced."

Competence Center D – General Manager

The last three bundles combine Computing technologies with Network and sharing technologies (B8), Data processing technologies (B9), or with both of them (B10). Generally described applications are those related to smart manufacturing, even though our informants also mentioned smart working as a potential way of using these technological combinations. The benefits mainly concern plant performance, in particular the efficiency, effectiveness and quality of the production process. The CEO of Competence Center A made the following observation:

"A possible implementation of a Digital Twin is the real-time modeling and simulation of the mechanical or intra-logistic production process using data from production systems and supplied by IoT sensors and gateways. When these data are analyzed by means of Artificial Intelligence techniques, it is possible to predict any deviations from the targets, and any increases or decreases in performance and product quality problems, thus optimizing the production processes from both a technological and an economic point of view."

Competence Center A - CEO

5. Discussion

The aim of this research has been to explore the possible complementarities between I4.0 technologies, as well as their relationship with the performance of firms, by executing interviews with 13 Italian I4.0 experts and then triangulating the results with relevant secondary data. Our findings show that companies can combine I4.0 technologies in different bundles to improve their performance, with emerging patterns of technological complementarity. Moreover, while some performance benefits can be achieved also when technologies are implemented in isolation, their joint adoption seems to provide the broadest and richest benefits, identifiable by taking a systems theory perspective. We discuss these two main findings in the next paragraphs of the section. In section 5.1, we develop an original model that links I4.0 technologies with firm performance through three kinds of complementarities: platform, hybrid and full complementarity. In the following section, we make instead a more thorough discussion on the performance effects of scattered and joint I4.0 adoption, interpreting them with the systems theory lenses. Building on this evidence, we present two research propositions that summarize the main takeaways of our research.

5.1. Towards a complementarity model of industry 4.0 technologies

A first important result of this research is the identification of different bundles of I4.0 technologies. Interestingly, it emerges that not all the possible combinations of technologies can be mapped into specific bundles (see Table 6) or can be judged valuable in a systematic implementation of I4.0. In fact, it has emerged that only Data processing technologies (e.g., big data and analytics) and Network and sharing technologies (e.g., IoT) are combined with all the other technology classes. Building on this, we can argue that Data processing technologies and Network and sharing technologies constitute fundamental building blocks enabling the other classes of technologies to be considered for companies aiming to implement a bundle of I4.0 technologies. Building on previous operations management (Meyer and Lehnerd, 1997; Simpson and Siddique, 2007) and technology strategy literature (Cusumano and Gawer, 2002), we suggest that such technologies operate as platforms for the other I4.0 technologies, playing the role of the so-called General Purpose Technologies as recalled by Culot et al. (2020). The other classes of technologies, i.e., Digital production technologies (e.g., additive manufacturing and 3D printing), Visualization technologies (e.g., augmented reality) and Computing technologies (e.g., cloud computing) are shown to be adopted in combination only with one or both the two fundamental building blocks (i.e., platform technologies). We identified three kinds of I4.0 complementarities from these considerations and results, and categorized them into the original model shown in Fig. 2.

By combining platform technologies with each other, the first kind of complementarity is obtained, namely, **platform complementarity**. Platform complementarity derives from a combination of technologies, such as Cloud computing and AI, or IoT and Big data analytics, and it enables an improvement of several performance dimensions, ranging from efficiency in production processes, to the introduction of new

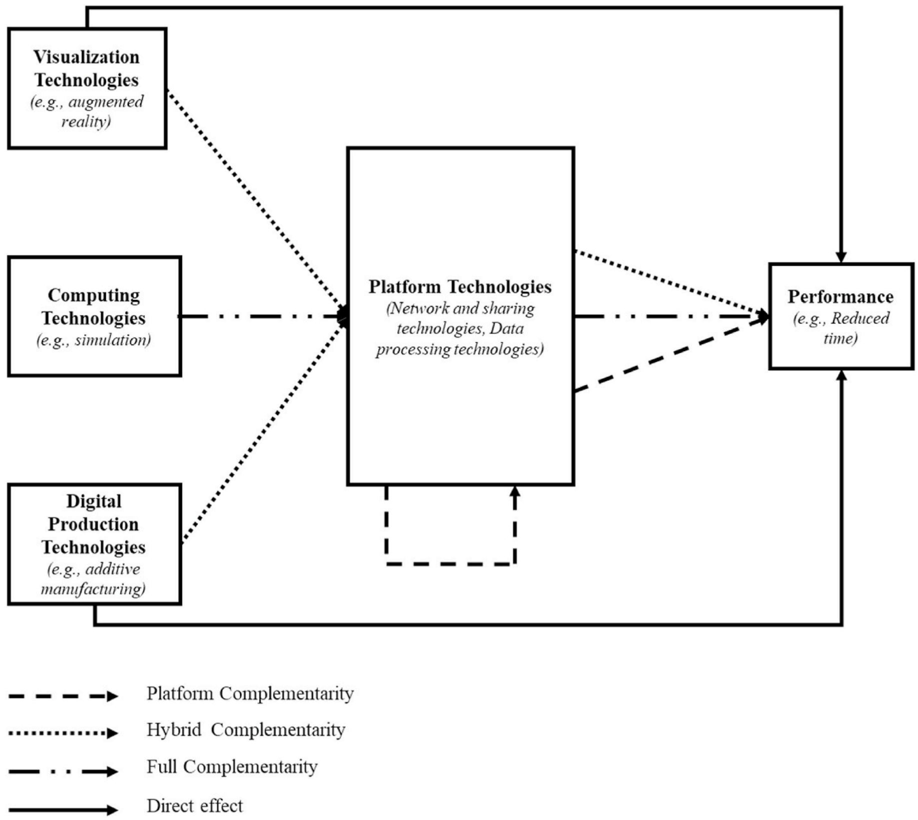

Fig. 2. A model of technological complementarity among Industry 4.0 technologies.

features on products on which the firm can build to increase its revenues. More in general, this platform complementarity follows a process of knowledge recombination through knowledge grafting (Nag et al., 2007; Lanzolla et al., 2021), which entails opportunities to improve processes, work organization (Zuboff, 1988), and predictions about future events (Agrawal et al., 2018). By combining technologies to extract, collect and analyze huge amounts of data, companies can indeed support the decision-making process of firms, thus increasing their competitive advantage.

A second typology of complementarity that can arise through the implementation of I4.0 technologies is **hybrid complementarity**, which derives from the combination of platform technologies with either Visualization or Digital production process technologies. Hybrid complementarity originates from the multifaced impact that the implementation of some I4.0 technologies may have a firm's performance (Zheng et al., 2021). Our results, in fact, point to evidence that some technologies have both a single impact and a joint impact on the performance of a firm. This means that both the adoption (and use) of such technologies in isolation or jointly with other platform technologies may exert an impact on performance. For example, the use of cobots for an assembly task is further enhanced by Artificial Intelligence by reducing the cycle time rate and thus improving operational efficiency. However, the implementation of cobots as stand-alone technologies can easily improve the working conditions of line workers (i.e., they provide ergonomic benefits), thus increasing the workers' productivity and safety, and also increasing revenues and reducing costs for the company (Cohen et al., 2021). Hybrid complementarity intrinsically entails the combination of technologies in a causally ambiguous (Reed and DeFillippi, 1990) and inimitable (Rivkin, 2000) way.

Finally, the joint combination of Computing technologies with platform technologies identifies the third type of complementarity that has emerged from this study: **full complementarity**. Full complementarity involves technologies (i.e., Computing technologies) which may not impact performance, should they be adopted in isolation. For instance, it is difficult for simulation technologies to have a beneficial impact on a firm's operations if real-time data are not collected from the operational systems (e.g., through IoT). Indeed, the combination of such groups of technologies represents a technological system that is based on multiple techniques and functionalities that apply data for value creation in specific forms (Klingenberg et al., 2019).

The versatility of application of I4.0 technologies is also demonstrated by the broad coverage of applications that is associated with the different complementarities described above. In fact, the technologies that are considered in both platform and hybrid complementarities can be applied to generate benefits over a broad domain of applications, such as smart manufacturing, smart working and smart products. On the other hand, full complementarity has a more limited domain of application, as it can only be created in the context of smart manufacturing and smart product applications. Overall, the broadness of the potential applications of technology complicates the understanding of companies on how such technologies should be implemented (Sony and Naik, 2020). This result further supports the idea that firms should develop a strategy or a roadmap to understand the correct collocation (application) of the technologies implemented within the firm, as suggested by Ricci et al. (2021).

5.2. *Performance effects of scattered and complementary I4.0 adoption*

A first interesting insight linked to the I4.0 performance effects can be derived from an analysis of the application areas. The majority of impacts that have emerged in the results of the Smart manufacturing application for both single technologies (Table 5) and bundles (Table 7) confirm that I4.0 is a phenomenon that has its greater impact in enabling operational processes, such as flexibility, cost and quality (Enrique et al., 2022b; Gillani et al., 2020). Lower, but not negligible, attention is instead paid to enhancing the smart working area, considering fewer human efforts, in terms of decision-making processes, well-being and ergonomics (Kadir and Broberg, 2020). Moreover, there is growing concern about the value creation opportunities of smart products, especially in terms of the integration of (new) services and capabilities (Porter and Heppelmann, 2014), enabled by such technologies as Data processing and Network and sharing technologies. Conversely, the broader benefits at inter-organizational and supply chain level did not emerge from data analysis. Several studies have demonstrated the fundamental impacts of I4.0 when extended to interactions and collaborations with supply chain echelons and processes (e.g., Fatorachian and Kazemi, 2021; Hofmann and Rüsch, 2017). A few experts mentioned some possible data collection and sharing extension opportunities with suppliers and customers, but none of the use cases focused on this specific area. On the one hand, this result could be interpreted as suggesting a still low awareness of many companies about the specific complementarities that can be reached outside organizational boundaries, thanks to the implementation of a technological structure to support networking among actors (Benitez et al., 2020). On the other hand, many manufacturing companies might not perceive performance outcomes, such as end-to-end visibility, as a priority for implementing one or a combination of I4.0 technologies.

Overall, by combining the results on the performance effects of scattered (Table 5) and complementary adoption (Table 7) of I4.0 technologies, it is possible to develop a summary framework showing the multifaceted nature of the Industry 4.0 technology-performance link that emerged from our analysis. The framework, reported in Fig. 3, distinguishes the direct impacts of the five classes of 4.0 technologies and the (joint) impact they exert when combined with one or more platform technologies (i.e., Network and sharing technologies and/or Data processing technologies). The three complementarity types described in the previous section are also highlighted in the framework.

While many studies (e.g., Hahn, 2020) argue that 4.0 technologies should work only in bundles (thus implying a complementarity between technologies), this research indicates that even the adoption of technologies in isolation can benefit companies. Fig. 3 indeed shows that almost all performance outcomes can be potentially achieved by implementing single technologies, even though their impact seems to be limited. This result may explain why many firms experience scattered technological adoption (e.g., Cirillo et al., 2021; Ricci et al., 2021); as well as why Industry 4.0 implementation is often described by several technologies, but not in a systematic way (Klingenberg et al., 2019).

However, although the integration of different solutions does not seem strictly necessary to unleash a digital transformation, the results seem also to support the concept of complementarity (Milgrom and Roberts, 1990) within the I4.0 context, namely that bundles of technologies have a higher and broader effect on performance than adopting the same technologies in isolation. All the bundles have been shown to enable a larger number of applications, as well as larger dimensions of performance outcomes. This is evident from the comparison between the results achieved for a single technology-performance link and those for the bundles and related impacts. For example, when Visualization technologies are implemented in isolation, they can positively affect

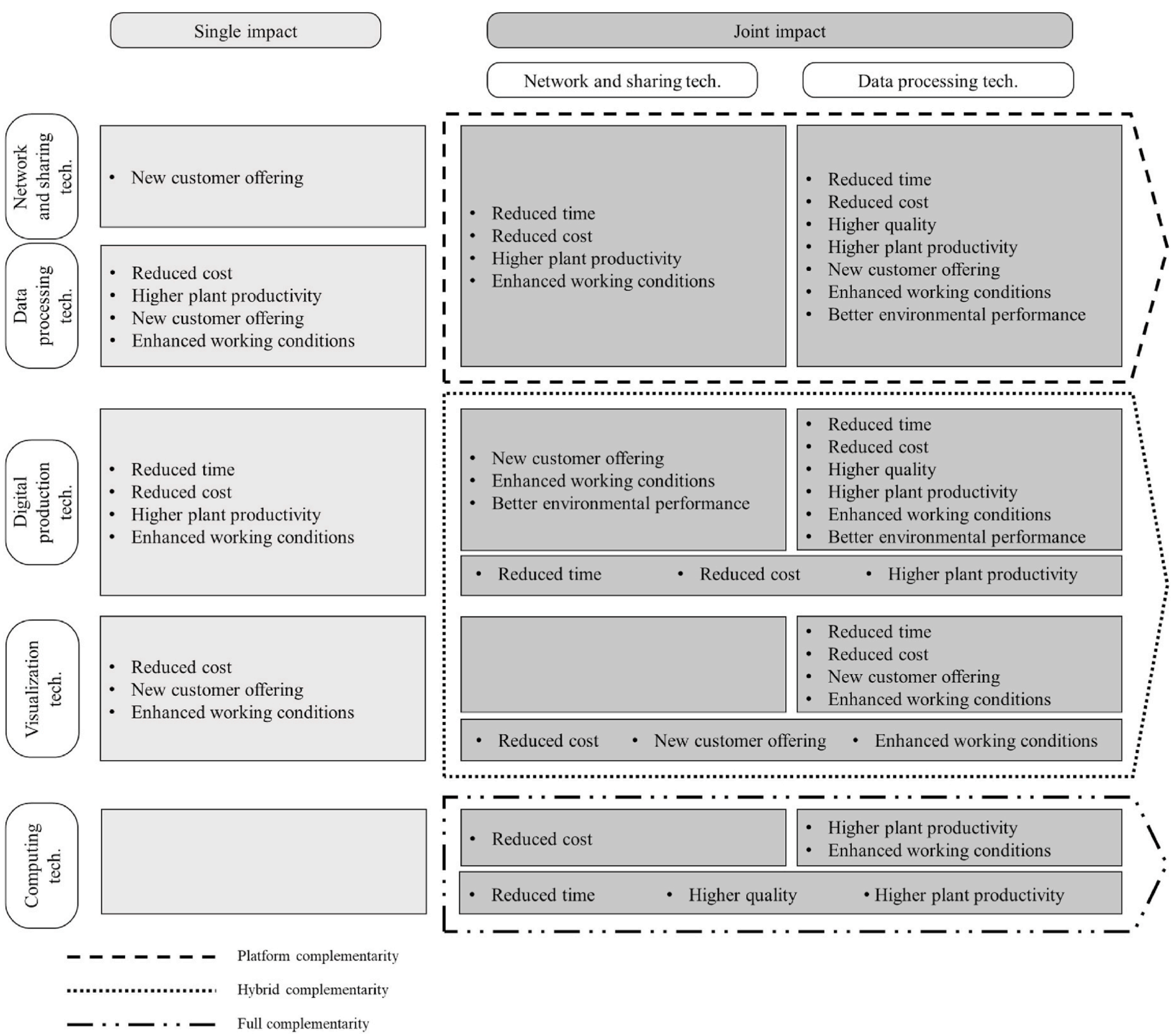

Fig. 3. A framework depicting Industry 4.0 technology-performance link.

outcomes such as cost, customer offering and working conditions, as shown in Fig. 3. However, if combined with Data processing technologies, the aforementioned benefits of Visualization technologies alone are enriched by a potential reduction of plant development time, thus broadening their range of action. These considerations lead us to formulate Proposition 1 as follows:

P1: The scattered adoption of Industry 4.0 technologies leads to some performance improvements, but this impact is limited if compared with the potentialities offered by a complementary I4.0 adoption.

The comparison of our results with the principles of systems theory allows to provide further original discussion on the I4.0-performance link. First of all, as suggested by P1, our results confirm the relevance of systematically interpreting Industry 4.0 as a complex system characterized by various sophisticated components that need to be integrated, as suggested by Benitez et al. (2020) and Fatorachian and Kazemi (2021). The main benefits of Industry 4.0 are indeed determined by the joint effect of all constituent subsystems (i.e., I4.0 technologies) working together. Second, the findings also point out that, in the I4.0 context, the notion of complementarity entailed by the systems theory is more complex and articulated than the mathematical illustration that the whole (i.e., the system) is greater than the sum of its parts (Xu, 2020). The joint adoption of technologies may indeed create a synergy whose effects cannot be explained by looking only at the benefits of the single technologies adopted alone. The first evidence of this fact is provided by the Computing technologies that, alone, do not activate any performance benefit and thus only work in synergy with one or more Platform technologies. Additional examples can also be found. For instance, if we look at the isolated adoption of Digital production process technologies (e.g., cobots) and Data processing technologies (e.g., artificial intelligence), we see from Table 5 and Fig. 3 that they can lead to benefits such as reduced throughput time and increased production efficiency respectively. However, when implemented together as a bundle, they enable additional and new outcomes, such as higher product quality and better environmental performance. Similarly, time performance is enhanced in multiple ways when this hybrid complementarity is adopted, reducing not only the throughput time, but also the plant development time. From a theoretical viewpoint, the principle of systems' wholeness in Industry 4.0 indicates that the whole could differ from the sum of the impacts reached with the single technologies, enabling benefits not reachable by any scattered adoptions. These elaborations on systems theory principles lead us to formulate Proposition 2:

P2: The benefits activated by the joint adoption of Industry 4.0 technologies are not necessarily greater but (also) wider than those activated by the scattered adoption of the technologies in isolation.

A final observation worth discussing is that the results of the study include very few references to financial performances at a company level. Some experts have mentioned the benefit of implementing I4.0 technologies on profitability and return on investments, but there is evidence of an indirect effect that is not linked directly to specific applications. For example, the integration of Data processing technologies with Network and sharing technologies in a bundle aimed at collecting, elaborating and sharing data from products and customers in order to offer smart products, will not only improve customer experience and thus increase the perceived quality, but also subsequently result in extra revenues. Kamble et al. (2020), in fact, stated that technologies that lead to an improvement in product quality and customer service satisfaction increase the overall efficiency of a firm. The few results on financial outcomes could be explained by the limited time window since technology implementation to evaluate the most recent I4.0 projects, or the bias of companies that are still reluctant to share performance data (Duman and Akdemir, 2021). Nevertheless, we argue that the adoption and usage of a technology in isolation, or a bundle of technologies, in a specific application domain (e.g., smart manufacturing) can impact the overall company performance via a systematic I4.0 application.

6. Conclusions

This study develops the concept of complementarity in the I4.0 context, exploring the synergistic effects of enabling technologies into bundles, and valorizing these bundles based on their link with company performance in multiple application areas. Bundles are conceived as complex systems of physical artifacts, characterized by a variety and thus different technologies with different instances (Saviotti, 1986), namely the I4.0 technologies and their operational functionalities enabling 'specific intelligence'. By analyzing the relationship between the I4.0 technologies themselves and the events they produce, i.e., the performance outcomes, through their interaction, as suggested by Mele et al. (2010), we could identify and explore three different types of I4.0 complementarities, enhancing their more holistic understanding and the related performance effects.

This research provides several contributions to literature. First, the results presented in this study respond to the direct call by Culot et al. (2020), for further research on the complementarity between I4.0 technologies. In particular, the multifaced platform, as well as the hybrid and full complementarities that result from different combinations of I4.0 technologies, extend and provide further nuance to the adoption patterns implemented by firms (Agostini and Nosella, 2019), and explain the high heterogeneity of adoption among firms (Ricci et al., 2021). Moreover, in the same way as some adoption studies (e.g., Agostini and Filippini, 2019), this research recalls the importance of firm strategy in implementing I4.0 technologies in production processes.

Second, this research deals with the performance effects of I4.0 technologies, a topic still highly debated in the literature (Enrique et al., 2022a; Szász et al., 2020). By identifying specific performance outcomes that are affected, deriving from both a scattered and a combined adoption of I4.0 technologies, it sheds light on the main (and also emerging) areas of impact that should be considered in the many opportunities an I4.0 transformative path offers companies. Furthermore, although previous literature (e.g., Hahn, 2020) argued that I4.0 technologies should only work in bundles (thus implying a complementarity between technologies), this research indicates that even the adoption of technologies in isolation can have benefits for companies, as shown by the several examples provided in Table 5 and Fig. 3.

Finally, from a theoretical viewpoint, this research contributes to the current streams of I4.0 literature by adopting the systems theory lens (Lawrence and Lorsch, 1967; Mele et al., 2010) to identify technologies, areas and mechanisms of complementarity, and summarizes them in a theoretical framework. We contribute to the theory by showing that I4.0 transformation patterns should be considered in both terms of impacts on the single subsystems, i.e., with single I4.0 technology linked to specific performance, and also, and especially, in terms of supra-systems, i.e., the application areas and the performance at company level. The systems theory lens guided the investigation on the variety of technologies, their functionalities, and their relationships, mapped as dynamic and not structural (Mele et al., 2010). These bundles can provide different contributions to the needs of the supra-systems, i.e., the application areas and the overall company, thus unleashing multiple ways of combining them into greater but also wider performance to be potentially reached. Here, we extend the previous studies (e.g., Dalenogare et al., 2018; Enrique et al., 2022b) that identify possible groups of technologies and the effects of these single groups on performance or specific manufacturing objectives, by pointing out the richness and multiplicity of the joint adoption of I4.0 technologies towards complementarity. Results show the emergence of three types of complementarities, which lead to significant performance improvements over broader application areas, thus demonstrating the importance of a holistic approach toward performance improvements (Fatorachian and Kazemi, 2021), which goes beyond the mathematical illustration that the concept of the whole (i.e., the system) greater than the sum of its parts (Xu, 2020).

From a practical point of view, this study has aimed to increase managers' awareness of complementarities and the related performance effects, but also to support them in addressing their investments in emerging technologies. The results of our study stress the need to implement specific technologies to increase performance outcomes.

In particular, as far as platform technologies (i.e., bundles of Network and sharing and Data processing technologies) are concerned, this study informs managers that such bundles represent the solution with the highest level of versatility: they can increase plant productivity, improve quality, time and cost performance, but also enhance the service level offered to customers, obviously depending on the type of collected, stored and analyzed data. As for the other I4.0 technologies, and the Digital production process and/or Visualization technologies in particular, managers should be aware that the benefits that can be obtained are limited if they are implemented in isolation. Indeed, our results suggest that only when complemented with one or more platform technologies, do they enable more application areas and broader performance outcomes. Clearly, such a decision should be carefully weighted according to the firm's strategy.

Based on these elements, our research provides detailed guidance to managers on the improvement of specific outcomes. Fig. 3 depicts the performance outcomes that can be obtained when different groups of technologies – and their functionalities – are combined in multiple ways. This allows managers to increase their awareness of which specific technologies provide a specific desired outcome and provides a reference guideline to them to avoid technological adoption based on guesses, gut feeling, or experience which, often, may result in a weak decision-making approach.

This study is not free of limitations. Our results, being linked to the Italian context and the perspective of Competence Centers operating within Italy, may be subject to country specificities. Moreover, it may also have occurred that some combinations of technologies have not emerged because of this limitation. This limitation bounds the generalizability of our theory, but it does not diminish its value. The presence of platform, hybrid and full complementarities represents a result which deserves further investigation in future research. At the same time, there is in fact a paucity of data linking firm performance to the adoption of I4.0 technologies. Future research could use data - as they become available - to test and complement the complementarities that have emerged in this work, as well as to further verify whether some of them have superior effects than others. Moreover, future research can also leverage our results on the different kinds of complementarities to test whether a causal effect exists between these conditions and the several performance outcomes we identified. Finally, we envision further research to extend the results of this study to the impact of I4.0 complementarity on economic and financial performance. On this topic, our research seems to point toward an indirect effect of the adoption of different technologies/bundles belonging to the I4.0 paradigm, while we remain agnostic about the kind of dimensions that could be affected. Therefore, we solicit and urge the need for further studies to investigate this issue.

Data availability

The data that has been used is confidential.

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Appendix A. Summary of the interview protocol

Section A. General information of the interviewee

a. What is your role in the organization?
b. What does this entail?
c. How long have you been in this role?
d. How many years of working experience on Industry 4.0 do you have in total?

Section B. Industry 4.0 technologies and related applications

a. What are the technologies that characterize the Industry 4.0 phenomenon?
b. What are the applications of such technologies? In other words, what firm processes are mainly impacted by them? How?

Section C. Complementarities between Industry 4.0 technologies

a. Do Industry 4.0 technologies create synergies?
b. If yes, how can they be combined? Can you provide some detailed examples (i.e., specific technologies combination)?
c. What are the applications of such combinations?

Section D. Performance effects of Industry 4.0 technologies

a. What performance outcomes are mainly affected by each Industry 4.0 technology?
b. Do the combinations of Industry 4.0 technologies create complementary effects on performance (i.e., do they provide a surplus of benefits that cannot be explained considering only the performance effects of technologies implemented in isolation)? How?
c. What are the performance outcomes affected by such combinations?
d. Do you have any personal experience of companies you partnered with, where such combinations have led to significant performance changes/improvements? Why did the combinations (did not) work?

Section E. Closing remarks

a. Do you want to share with us any additional considerations on the topic we just discussed (i.e., how 4.0 technologies can be combined to develop certain applications and how they can impact business performance)?

Appendix B. List of the use cases analyzed in the research

#	Competence Center	Use case	Technologies (when specified) and (eventual) reasons for non-inclusion
1	F	A smartwatch for operator's safety	IoT, Big Data and Analytics
2	F	Artificial intelligence models for predicting sales in the textile industry	Artificial Intelligence
3	F	"Data driven prognostic" and "prescriptive maintenance" models for manufacturing	Cloud computing, Big Data and Analytics, Artificial Intelligence
4	F	Innovative data logger integrated in the battery pack for data acquisition, analysis and remote control of parameters	IoT
5	F	Digital Twin for the manufacturing industry	Digital twin, IoT, Artificial Intelligence
6	F	Intelligent sales and order management based on distributed AI.	Cloud computing, Artificial Intelligence
7	F	Mizubot4.0 to automate the loading materials process on an assembly line	Robot
8	F	Validating the manufacturing processes and performance of metal 3d printed, modular and smart heat exchangers. From prototypes to products.	IoT, Additive manufacturing
9	F	Safety through awareness	Augmented/Virtual Reality
10	B	Digital solutions for product customization and remote control	IoT, Additive manufacturing
11	B	Automation of the loading-unloading process and/or analysis of defects on compression molding presses for rubber soles	Cobot, Artificial Intelligence
12	B	Improving the performance of heat exchangers through additive manufacturing	IoT, Additive manufacturing
13	B	An innovative solution for predictive maintenance of an industrial equipment	IoT, Big Data and Analytics
14	E	Prevent health risky situations at work with the use of AI and machine learning	IoT, Artificial Intelligence
15	A	Work safety management with Industry 4.0 technologies	IoT, Big Data and Analytics
16	A	AI-based surveillance system for people detection & safe social distance detection	IoT, Big Data and Analytics
17	A	Business Process Management: a tool for monitoring and optimizing processes	Big Data and Analytics
18	A	Predictive maintenance: a proactive and automated approach	IoT, Big Data and Analytics
19	A	Analyses to predict, prevent and optimize: the use of IoT for business decisions	Cloud computing, IoT, Artificial Intelligence
20	A	Data analytics: extraction of energy consumption levels and their analysis in relation to production	IoT, Big Data and Analytics
21	A	Numerical optimization for industrial automation and logistics	IoT, Artificial Intelligence
22	A	Real-time optimization of workflows	Robot, IoT, Artificial Intelligence
23	A	Fast tracking, process monitoring and strategies driver	IoT, Artificial Intelligence
24	A	Predictive optimization: a solution to increase productivity	IoT, Big Data and Analytics
25	A	Image Recognition in the fashion industry	Artificial Intelligence
26	A	Image Recognition for quality control	Artificial Intelligence
27	A	Towards the digitization of industry at 360°	Robot, IoT, Cloud Computing, Big Data and Analytics
28	A	The universal Zero-coding solution for Industrial IoT projects	IoT, Big Data and Analytics
29	A	"In a box" IoT solution that simplifies data acquisition from industrial machines and plants	IoT, Cloud Computing
30	A	Smart Glasses to guide the operator on the operations to be performed	Augmented/Virtual Reality, IoT, Artificial Intelligence
31	A	IoT: the translation of corporate information into business	IoT, Cloud Computing
32	A	Updating legacy machines	IoT, Big Data and Analytics
33	A	The new customer experience	IoT, Big Data and Analytics
34	A	Digital DNA for a full digital transformation	IoT, Cloud Computing
35	A	Professional 3D printing and Windform materials for high-end UAV components	Additive manufacturing
36	A	Availability of qualified experts. Everywhere.	Augmented Reality
37	A	Knowledge Box: the solution to have a virtual assistant always with you	Augmented/Virtual Reality, Big Data and Analytics
38	A	Virtual reality & mixed reality: immersive interactive training	Augmented/Virtual Reality, Big Data and Analytics
39	A	Monitoring of operational processes in the industrial field with Artificial Intelligence algorithms	Artificial Intelligence
40	A	Assisted maintenance through Augmented Reality	Augmented/Virtual Reality, Cloud Computing, Big Data and Analytics
41	A	Virtual simulator: development, training & education	Augmented/Virtual Reality
42	A	Man-machine interaction: getting closer!	Cobot, Artificial Intelligence
43	A	Sensor Fusion for resilient self-driving vehicles	Robot, Artificial Intelligence
44	A	Ergonomic wearable support	Cobot, Artificial Intelligence
45	A	Process automation to reduce the Takt Time	Robot, Artificial Intelligence
46	A	From the prototype design to the production of the finished product	Additive manufacturing
47	A	Reconfigurable robotic processes	Robot, Artificial Intelligence
48	A	Adaptive robotics for preparing orders for shipment	Robot, Artificial Intelligence
49	A	Innovative packaging system for slabs	Robot, Artificial Intelligence
50	A	Object reorientation: modular and scalable grippers	Robot, Artificial Intelligence
51	A	Tailor made industrial robotic solutions	Robot, Artificial Intelligence
52	A	Automatic defect recognition	Robot, Cloud Computing, Artificial Intelligence
53	A	From virtual prototype to Hybrid Twin	Digital twin, IoT, Big Data and Analytics
54	A	Digital Twin and Artificial Intelligence for risk assessment	Digital twin, Artificial Intelligence
55	F	Additive Manufacturing-based Anti-icing System	Additive Manufacturing No performance described
56	F	Printing a satellite Propulsion System	Additive Manufacturing No performance described.
57	F	Filtering system for the abatement of black powder produced during brass processing	Additive Manufacturing No performance described

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#	Competence Center	Use case	Technologies (when specified) and (eventual) reasons for non-inclusion
58	F	Classifying components of an electronic board	Artificial Intelligence No performance described.
59	F	Real time location system for materials	No technology nor performance described
60	F	Creating and analyzing a database on compounds of natural origin	Big data and Analytics Other industry than manufacturing
61	F	Monitoring networks	No information on technology Other industry than manufacturing.
62	F	Improving packaging through AI	Artificial Intelligence Other industry than manufacturing
63	F	Detecting cross-contamination	No information on technology Other industry than manufacturing
64	F	Real time location system	No technology nor performance described.
65	F	Additive manufacturing monitoring system	Additive manufacturing Unclear indication of other technologies involved
66	F	Coolant analysis and control	No information on technology
67	F	Smart printing services for AM	Additive Manufacturing Unclear performance implications.
68	F	Architectural innovation in the automotive industry	No information on technology
69	B	Digital assessment service for firms	Unclear indication of the technologies involved
70	E	AI monitoring of harbors	Artificial Intelligence Other industry than manufacturing
71	E	Harbors control room	Digital twin Other industry than manufacturing
72	E	Advanced maintenance of harbors	Digital twin, augmented reality, IoT, Big data and Analytics Other industry than manufacturing
73	E	Improving the integration of harbors and cities	Artificial Intelligence Other industry than manufacturing
74	E	Digitalizing Harbors	Weak indication of the technologies involved Other industry than manufacturing
75	E	Improving cyber security in harbors	Unclear indication of the technologies involved Other industry than manufacturing
76	E	Asset supervision for predictive maintenance in transportation systems	IoT, Big data and analytics Other industry than manufacturing
77	E	Energy efficiency in urban contexts through ML	Artificial intelligence Other industry than manufacturing
78	A	Semantic search engines for text collections	Other industry than manufacturing
79	A	Sustainable mobility for Smart Cities	Other industry than manufacturing
80	A	Monitoring the health of a professional driver using Artificial Intelligence algorithms	Other industry than manufacturing
81	A	Control systems for autonomous driving based on real-time optimization	Other industry than manufacturing
82	A	API Management and Mediation Devices	Other industry than manufacturing
83	A	Precision medicine: layering Big Data for predictive purposes	Other industry than manufacturing
84	A	Solar thermal systems with predictive component control and maintenance system	Other industry than manufacturing
85	A	Advanced control software based on real-time numerical optimization	Unclear information on the technologies involved.
86	A	Cognitive human-robot interaction	Other industry than manufacturing
87	A	Microservice platform for healthcare needs	Other industry than manufacturing
88	A	Data retention: mandatory services for judicial authorities	Other industry than manufacturing
89	A	Decision Support System for the Implementation of Precision Farming	Other industry than manufacturing
90	A	Analysis of Financial News through proprietary algorithms	Other industry than manufacturing
91	A	Sparse Analytic Hierarchy: SAHP	Other industry than manufacturing
92	A	Artificial intelligence for the sharing economy	Other industry than manufacturing
93	A	Cloud computing as enabler of digital transformation	Cloud computing Unclear indication on performance
94	A	Environmental App for Nature and Citizens	Other industry than manufacturing
95	A	Rethinking physical space with Data Intelligence	Other industry than manufacturing
96	A	Smart Network: battery-powered wireless sensor network	Other industry than manufacturing
97	A	5G within everyone's reach	Other industry than manufacturing
98	A	SCADA IDS: Framework for identifying cyber threats on SCADA systems	Other industry than manufacturing
99	A	Assessing the level of IT security in companies	Other industry than manufacturing
100	A	How blockchain ensures traceability and security	Other industry than manufacturing
101	A	Value based integrated care	Other industry than manufacturing
102	A	Tracking processes in healthcare with IoT	Other industry than manufacturing
103	A	Unique and personal identifier: biometric fingerprint	Other industry than manufacturing
104	A	Success-oriented supply chain	Few details to understand the context and the technologies
105	A	IoT for the Development of Precision Controllers and Precision Farming	Other industry than manufacturing
106	A	Quality under control	Few details to understand the context and the technologies
107	A	Indoor Navigation	Other industry than manufacturing
108	A	Indoor localization	Other industry than manufacturing
109	A	Vehicle tracking and tracing	Other industry than manufacturing
110	A	Epidig: Privacy-compliant contact tracing system	Other industry than manufacturing
111	A	Indoor radiolocation method with passive UHF-RFID technology	Few details to understand the application context and the performance implications
112	A	Interferometric radar ensuring 24-h monitoring	Other industry than manufacturing

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#	Competence Center	Use case	Technologies (when specified) and (eventual) reasons for non-inclusion
113	A	End-to-end digitization of a machining and assembly line	Other industry than manufacturing
114	A	Portable control unit for precision agriculture	Other industry than manufacturing
115	A	Non-invasive exhaled air collection device: Pneumopipe	Other industry than manufacturing
116	A	Multi-sensor system for biological fluid testing	Other industry than manufacturing
117	A	Multi-sensor system for food characterisation	Other industry than manufacturing
118	A	FLUTE: Sampling system for monitoring cured food products	Other industry than manufacturing
119	A	Wireless motion sensing node	Other industry than manufacturing
120	A	Enabling the human-machine interface in augmented reality technology solutions	Few details to understand the context and the technologies
121	A	Energy optimization and waste management software	Few details to understand the context and the technologies
122	A	Parkingview: when IoT enters everyday life	Other industry than manufacturing
123	A	Plug&Play: the largest library of connected objects	Few details to understand the context and the technologies
124	A	Photovoltaic installations on depleted landfill lots and water mirrors	Few details to understand the context and the technologies
125	A	Testing of innovative 3D printing materials	Few details to understand the context and the technologies
126	A	Zerowaste Project	Few details to understand the context and the technologies
127	A	Rapid prototyping and safety of medical devices	Other industry than manufacturing
128	A	3D reconstruction of real environments navigable through way points	Other industry than manufacturing
129	A	Smart museums and art venues	Other industry than manufacturing
130	A	Virtual and reconstructed Reality for Safety at Work	Augmented reality Unclear indication on performance
131	A	Cognitive rehabilitation in 3D Virtual Reality	Other industry than manufacturing
132	A	Objective measurements for the validation of medical devices	Other industry than manufacturing
133	A	Waste minimization, dose reduction and safety improvement in decommissioning	Other industry than manufacturing
134	A	Risk mitigation for workers in hostile environments	Other industry than manufacturing
135	A	Robotic hand: intelligent, powerful, versatile	Other industry than manufacturing
136	A	Underwater robotics for monitoring docks and port areas	Other industry than manufacturing
137	A	Robotic surgical navigation for neurosurgery and spinal surgery	Other industry than manufacturing
138	A	Robotic biomolecular diagnostics - Diagnostic system for COVID 19	Other industry than manufacturing
139	A	Human-digital interface	Other industry than manufacturing
140	A	Autonomous robots for intelligent inspection in confined spaces	Other industry than manufacturing
141	A	Optics applied to process automation	Other industry than manufacturing
142	A	Snake robot for inspection and service in hostile environments	Other industry than manufacturing
143	A	Using robots to improve the travel experience	Other industry than manufacturing
144	A	Making banking compelling	Other industry than manufacturing
145	A	Autonomous Indoor and Outdoor Navigation for Service Robots	Other industry than manufacturing
146	A	Programmable humanoid robot in assembly kit for entertainment and education	Other industry than manufacturing
147	A	14C detection based on infrared laser light	Unclear technologies
148	A	Test bench oil pumps for servo brake	Unclear technologies
149	A	HYDRO test bench	Unclear technologies
150	A	Tailor-made test bench: CO2 permeation test	Unclear technologies
151	A	PAM-STAMP: sheet metal stamping simulation	Unclear technologies
152	A	Product and process innovation: from concept to market	Unclear technologies

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