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REVIEW ARTICLE

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A cross-sectorial review of industrial best practices and case histories on Industry 4.0 technologies

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Abstract

Industry 4.0 (I4.0) was introduced in 2011, and its advanced enablers strongly affect industrial practices. In the current literature, while several papers offer general reviews on the topic, contributions exploring the evidences coming from the implementation of I4.0 in multi-sector Small and Medium Enterprises (SMEs) and large enterprises are few and expected. To address this gap, a comprehensive review of the main I4.0 enabling technologies is conducted, focusing on implementation experiences in companies belonging to different sectors. Forty (40) real case studies are analyzed and compared. The results show that 63% of the identified applications involve large enterprises in the transport sector, that is, automotive, aeronautics, and railway, adopting a structured set of enabling technologies. SMEs engaged in I4.0 projects primarily belong to the mechanical engineering sector, and 37% of such projects deals with the preliminary feasibility analysis of introducing a single enabling technology. Conclusions and trends guide researchers and practitioners in understanding the implementation level of I4.0 technologies.

KEYWORDS

cross-sectorial review, digitization, enabling technologies, industrial revolution, Industry 4.0, smart manufacturing

1 | INTRODUCTION AND RESEARCH POSITIONING

Industry 4.0 (I4.0), also known as the fourth industrial revolution, is a topic of great interest in both Academia and Industry. The term was first introduced in 2011 at the Hannover Fair in Germany to highlight the global transformation of industrial companies through a set of emerging enabling technologies, such as the Internet of Things (IoT), artificial intelligence (AI), and augmented reality (AR). Implementing such technologies was expected to change the production systems by transforming analog and centralized workflows into digital and decentralized smart production processes. Potential benefits include the productivity increase, the minimization of the greenhouse gas emissions generated by the production processes, as well as more intelligent and more adaptive, sustainable and human-centered manufacturing and assembly systems.[1–5] However, as for any disruptive technology upgrade, a set of barriers slows the transition toward I4.0. Among these, the literature explored the lack of a skilled workforce in these new technologies, conflicts among operators due to changing and dynamic industrial contexts, data security, shortage of financial resources and expertise, especially in Small & Medium Enterprises (SMEs), as well as insufficient degree of process standardization. Among them, the lack of a clear digitization vision and the shortage of resources are the most significant barriers to I4.0 adoption in developing and developed countries.[4] The development of shared standards and public regulations could facilitate the transition toward

I4.0 in the developing countries, while more advanced technological infrastructures are required to promote its adoption in the developed countries.[4]

According to a recent PricewaterhouseCoppers (PwC) survey involving more than 2000 industrial companies worldwide,[6] the number of companies that will adopt digital strategies and technologies is expected to double, on average, from 33% to 72% in the next coming years. I4.0 adoption will positively impact on cost reduction (with an average reduction, per year, equal to 3.6% and an efficiency increase equal to 4.1%) and higher revenues to an extent close to 2.9% per year. Moreover, SMEs significantly differ from large companies in terms of availability of financial resources, use of advanced manufacturing technologies, research and development capability. These differences lead to different approaches in adopting the technologies introduced by the I4.0 revolution and in the ease of their implementation. While several articles offered general literature reviews, critical investigations on I4.0 technologies implementation in multi-size and multi-sector companies are missing and needed to map the current level of applicability of I4.0 technologies. This research gap justifies the present study.

To position this paper in the current literature context, relevant recent reviews on I4.0, published in high-ranked journals in the field of industrial engineering, are investigated. Six main research streams, representing the focus of the current research, are identified, and the selected papers are assigned to one or more of them:

- ✓ Stream #1: General review on I4.0 concept;
- ✓ Stream #2: Review on I4.0 enabling technologies;
- ✓ Stream #3: Review on I4.0 and production management;
- ✓ Stream #4: Review on I4.0 and supply chain management;
- ✓ Stream #5: Review on I4.0 and sustainability;
- ✓ Stream #6: Review on I4.0 maturity models and applied research.

These streams are identified starting from the content of the selected papers. Table 1 highlights the mapping between the selected reviews and the six research streams. In this table, the articles are ordered according to the year of publication to track the evolution over the years of the topic.

Although the concept of I4.0 was introduced in 2011, papers published in high-ranked journals appeared since 2017, and the publication trend is increasing, proving the relevance of this industrial revolution according to the rapid transformation of the market in recent years. Figure 1 presents the paper sources. Relevant publications in the International Journal of Production Research, Computers in Industry, Computers & Industrial Engineering, and the International Journal of Production Economics cover up to 60% of the selected review papers.

Table 1 shows that most of the selected papers reviews the literature on I4.0 from a general perspective, that is, Stream #1, highlighting its main definitions, tools, and approaches used for its implementation. Papers falling in Stream #2 attempt to identify the most widespread technologies enabling this revolution. Papers in Stream #3 explore the link between I4.0 and the production management theory. Less investigated streams are the link between I4.0 and supply chain management, that is, Stream #4, between I4.0 and sustainability, that is, Stream #5, and critical reviews on I4.0 applied research, that is, Stream #6.

The presented analysis shows that the existing reviews on I4.0 investigate links and synergies between this topic and specific operations management areas and/or the achievement of a set of key performance indicators, such as the impact of I4.0 on sustainability, ergonomics, and production. The presence of few studies in Stream #6 clearly shows the need of contributions examining the implementation of I4.0 technologies in industrial companies, both SMEs and large enterprises, and mapping the most involved industrial sectors and the most frequently adopted technologies.

To fill this gap, this paper falls in Stream #6, and presents an updated survey on a large set of industrial case studies including both SMEs and large enterprises worldwide, offering a clear understanding of the current implementation level of I4.0 technologies and highlighting the most widespread and implemented. Therefore, a main contribution of this paper is to provide knowledge of real interest to researchers and industrial practitioners involved with, or contemplating, I4.0 deployment projects.

The remainder of this paper is organized as follows: the next Section 2 presents the critical analysis on I4.0 technology implementation in industry, while Section 3 deeply discusses the identified industrial applications. Finally, Section 4 concludes the paper with a final summary and remarks.

2 | CRITICAL ANALYSIS ON INDUSTRY 4.0 TECHNOLOGY IMPLEMENTATION IN INDUSTRY

This section aims at presenting and discussing the available contributions focusing on the implementation of I4.0 technologies in real operative industrial settings to identify the main features of the involved companies, in terms of size and industrial sectors, and the most frequently adopted enabling technologies.

The enabling technologies refer to a set of transversal applications supporting effective and accurate engineering decision-making in real-time, for example, in the production processes (manufacturing and assembly), to pick up information, and to store data.[59] Based on the analysis of the recent literature and industrial standards,[60] the I4.0 enabling technologies can be classified into nine main contributions, listed and described in Table 2.

Although all these technologies play a crucial role in managing modern industrial complexity, the first three, that is, advanced manufacturing solutions, additive manufacturing (AM), and AR, rise as front-end technologies and are the most analyzed and explored by both scientific and industrial communities.[59,61] The remaining are ICT-oriented technologies, implemented to enhance the real-time data exchange among all the production system physical and logical components in a secure way.

2.1 | Database setting

Academic databases and specific industry and consulting companies' websites are explored to identify and collect successful case studies about the implementation of I4.0 technologies. Regarding the

TABLE 1 Recent reviews on I4.0: Stream classification.

Author(s)	Year	Stream #1	Stream #2	Stream #3	Stream #4	Stream #5	Stream #6
Nguyen Ngoc et al.[7]	2022			✓			
Patyal et al.[8]	2022					✓	
Bittencourt et al.[9]	2021			✓			
Lee and Lim[10]	2021	✓					
Zheng et al.[11]	2021		✓				
Nakagawa et al.[12]	2021	✓	✓				
de Paula Ferreira et al.[13]	2020		✓				
Sanchez et al.[14]	2020		✓				
Ivanov et al.[15]	2020			✓			
Oztemel and Gursev[16]	2020		✓				
Silvestri et al.[17]	2020			✓			
Osterrieder et al.[18]	2020	✓					
Raj et al.[4]	2020	✓					
Bueno et al.[19]	2020		✓	✓			
da Silva et al.[20]	2020					✓	
Beier et al.[21]	2020					✓	
Abdirad and Krishnan[22]	2020				✓		
Ghobakhloo[23]	2020					✓	
Calabrese et al.[24]	2020	✓					
Masood and Sonntag[25]	2020		✓				✓
Nunez-Merino et al.[26]	2020			✓	✓		
Vianna et al.[27]	2020		✓				
Rosa et al.[28]	2020					✓	
Zonta et al.[29]	2020			✓			
Parente et al.[30]	2020			✓			
Culot et al.[31]	2020	✓					
Hughes et al.[32]	2020	✓					
Dolgui et al.[33]	2019			✓	✓		
Li et al.[34]	2019			✓			
Sony and Naik[35]	2019						✓
Ivanov et al.[36]	2019				✓		
Klingenberg et al.[37]	2019		✓				
Nascimento et al.[38]	2019					✓	
Kerin and Pham[39]	2019		✓			✓	
Rejikumar et al.[40]	2019	✓					
Nosalska et al.[41]	2019	✓					
Frank et al.[42]	2019		✓				✓
Castelo-Branco et al.[43]	2019						✓
Galati and Bigliardi[44]	2019	✓					
Manavalan and Jayakrishna[45]	2019		✓		✓		
Kamble et al.[46]	2018	✓					
Dallasega et al.[47]	2018				✓		
Buer et al.[48]	2018			✓			
Moeuf et al.[49]	2018						✓

(Continues)

TABLE 1 (Continued)

Author(s)	Year	Stream #1	Stream #2	Stream #3	Stream #4	Stream #5	Stream #6
Dalenogare et al.[50]	2018		✓				
Mittal et al.[51]	2018						✓
Lezzi et al.[52]	2018		✓				
Badri et al.[53]	2018			✓			
Xu et al.[54]	2018	✓					
Fettermann et al.[55]	2018		✓				
Ghobakhloo[56]	2018	✓					
Liao et al.[57]	2017	✓					
Huang et al.[58]	2017					✓	

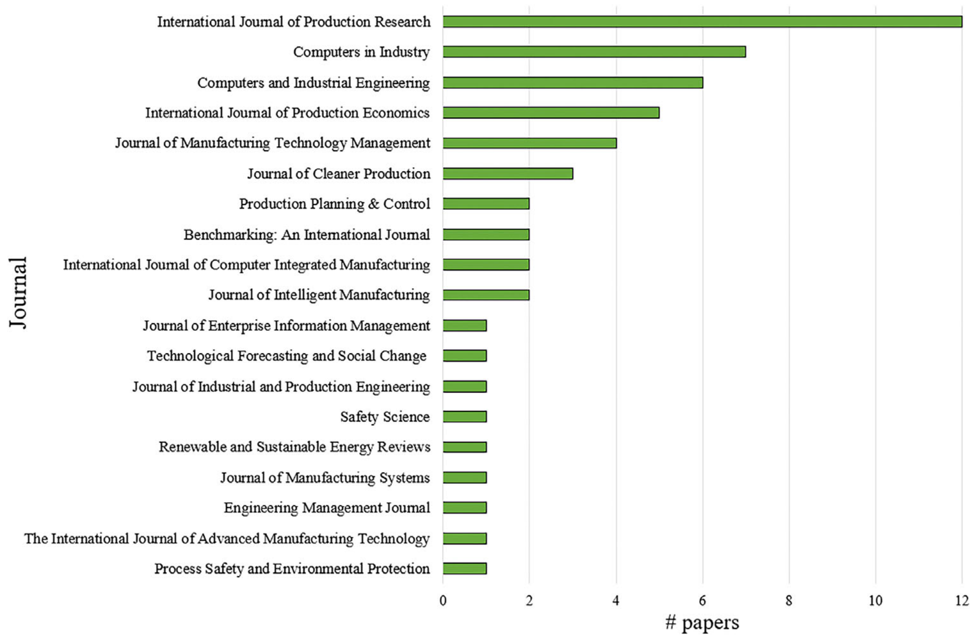

FIGURE 1 Review database classification per publication journal.

first contribution category, relevant databases as Google Scholar (scholar.google.com) and Scopus (scopus.com) are used. Search keywords include three specific strings, that is, "*Industry 4.0 case study,*" "*Industry 4.0 industrial application,*" and "*smart manufacturing*" as basic terms for articles screening. This is because the focus of this paper is to explore scientific and industrial studies highlighting a real application case of at least one of the I4.0 enabling technologies. In a second stage of the analysis, as discussed in the next Sections, once the suitable studies are selected, we match them to specific I4.0 technologies to draw insights and conclusions.

The articles published in high-ranked international journals in the field of industrial engineering or in indexed international conference proceedings are selected for the analysis, getting 23 articles. It is important to mark that the present analysis is limited to the studies reporting real I4.0 technologies implementation cases. The second contribution source is by the extensive and comprehensive analysis of specific industry and consulting company online information and reports which were examined to identify successful I4.0 worldwide case studies. Globally, 40 representative industrial cases are collected and discussed. Table 3 lists all contributions in alphabetical order and their main characteristics, that is, I4.0 enabling technology/technologies implemented in the case study, the size and the industrial sector of the involved company, and a short description of the I4.0 project. In the analysis, the industrial sector and size classification provided by the European Commission (EU) is used.[62] According to the EU guidelines, SMEs are characterized by a maximum of 250 employees. Otherwise, in case of a greater number of employees, the company is considered as large.

Analyzing the presented applications (Table 3), 25, that is, 63%, are introduced in large enterprises, while the remaining 15, that is, 37%,

TABLE 2 Industry 4.0 enabling technologies.[60]

Enabling technology ID.	Enabling technology name	Enabling technology description
#1	Advanced manufacturing solutions	Autonomous and collaborative industrial robots Systems characterized by integrated sensors and standard interfaces
#2	Additive manufacturing	Modern 3D printing techniques for prototypes and spare parts 3D facilities for inbound logistics, e.g., inventory, and outbound logistics, e.g., transport, optimization
#3	Augmented reality	Augmented reality techniques and tools for production (manufacturing and assembly), logistics, and maintenance Display of supporting information through e.g., smart glasses and advanced devices
#4	Simulation	Simulation of value networks Digital twins of production systems
#5	Horizontal/vertical integration	Inter-company data integration Cross-company data integration
#6	Industrial internet	Networks of products and machines Horizontal and vertical communications among all the production system components (product, machines, people)
#7	Cloud	Management of big data volumes in open systems Real-time communication for production systems
#8	Cyber-security	Defending computers, servers, networks and data from malicious attacks
#9	Big data and analytics	Full evaluation of available data (from ERP, MES, etc.) Real-time decision-making support and optimization

are introduced in SMEs. This indicates that large enterprises are, so far, the companies most involved in I4.0 transformation projects, in line with a recent PricewaterhouseCoopers (PwC) survey,[6] which relieves that I4.0 solution suppliers sell more to companies with more than 2000 employees (41%), to companies between 100 and 2000 employees (39%) and, finally, to companies with fewer than 100 employees (20%). Next Figures 2 and 3 show such classification together with the specific enabling technologies explored in the collected I4.0 projects.

Analyzing the case of large enterprises, 9 case studies, that is, 36%, concerns multi-enabling technologies applications; 7, that is, 28%, focus on AM; 3, that is, 12% on industrial internet; 3, that is, 12% on AR; 2, that is, 8%, on big data & analytics and, finally, 1, that is, 4%, on advanced manufacturing solutions. Such results highlight that, in large enterprises, most of the implementation case studies concern the application of a set of enabling technologies as part of a structured project of innovation. In fact, according to Fritsch and Meschede,[96] in big-sized enterprises, it is expected to find a relevant part of R&D budget spent on product and/or process innovation. The case studies focusing on multi-enabling technologies applications face innovative and structured projects merging advanced manufacturing solutions, AM, and industrial internet technologies.

Focusing on SMEs, 3 case studies, that is, 20%, focus on the first enabling technology, that is, advanced manufacturing solutions; 3,that is, 20%, on AR; 4, that is, 26.7%, on industrial internet; 1, that is, 6.6% on big data & analytics while 4, that is, 26.7%, are multi-enabling technologies applications. Such multi-enabling technologies applications join, mainly, advanced manufacturing solutions and industrial internet technologies. Globally, more than 73% of such SMEs case studies concern the analysis and tentative implementation of a specific I4.0 technology rather than multi-technology implementations. Such a result is expected and in line with the financial features of SMEs, which often have a limited budget and the level of penetration of the new technologies is slower than that of large enterprises. A further relevant consideration is that, globally, among the nine standardized enabling technologies, advanced manufacturing solutions (enabling technology ID. #1), AM (enabling technology ID. #2), AR (enabling technology ID. #3) and industrial internet (enabling technology ID. #6) appear to be the most promising largely adopted by both SMEs and large enterprises.

Next Figure 4 links the identified case studies to the industrial sectors to which they belong, while Figure 5 links the company industrial sector to its size (large enterprises or SMEs), that is, the size of the circles representing the sectors is proportional to the number of case studies belonging to that sector.

The figures show that the mechanical engineering sector is the most involved in I4.0 implementation projects, especially involving SMEs, which collect 8 case studies in this sector out of a total of 15. It is immediately followed by the transport sectors, that is, automotive, aeronautical, and railway, especially involving large enterprises, collecting 19 case studies out of 25.

TABLE 3 Industry 4.0 case study classification.

Source, year	Main I4.0 technologies	Industry sector	Industry size	Main topics
Airbus Company[63]	Augmented reality	Aeronautics industry	Large	Development of iflyA380 app by Airbus to allow passengers to book flights, interact with aircraft and take a tour of the cabin ahead of time
Alexopoulos et al.[64]	Industrial internet	Mechanical engineering (machinery)	SME	Architectural design and development of an industrial IoT framework to realize services in Industrial Product and Service Systems (IPSS)
Barbosa et al.[65]	Advanced manufacturing solutions; Industrial internet	Mechanical engineering (rail supply industry)	Large	Integration in the company of cyber-physical systems and Intelligent Products (IP) to optimize the whole train life cycle and increase quality
	Advanced manufacturing solutions; Industrial internet	Electric and Electronic Engineering Industries	Large	Integration in the company of cyber-physical systems and Intelligent Products (IP) to improve production efficiency and product quality
BMW[66]	Additive manufacturing	Automotive industry	Large	Several applications of AM in BMW AG, e.g., to manufacturing two parts of i8 Roadster (convertible's roof bracket and the window guide rail)
Bortolini et al.[3]	Advanced manufacturing solutions	Mechanical engineering (machinery)	SME	Digitization of the production system (assembly line, products, and operators) to allow a real-time data exchange and system reconfiguration
Braccini and Margherita[67]	Advanced manufacturing solutions; Additive manufacturing; Industrial Internet	Mechanical engineering (machinery)	SME	Switching of the company from traditional to smart assembly line through IoT technologies and collaborative robots; digitization of the product design phase using 3D printing
Bysko et al.[68]	Augmented reality	Automotive industry	Large	Development of an innovative paint shop concept to reduce the bottleneck in the car paint shop
Castor[69]	Additive manufacturing	Aeronautics industry	Large	Use of 3D printing in Boeing to produce the antenna component, reducing its weight and production time, and for jets production
Castor[69]	Additive manufacturing	Aeronautics industry	Large	Airbus produced the first titanium parts through 3D printing for a serial production aircraft, e.g. Airbus A350 XWB
Castor[69]	Additive manufacturing	Aeronautics industry	Large	Use of AM by NASA for space exploration as a mean to lighten the load and reduce costs
Cohen et al.[70]	Advanced manufacturing solutions	Mechanical engineering (machinery)	SME	Digitization of the production system (assembly line, products, and operators) to allow a real-time data exchange and system reconfiguration
De Felice et al.[71]	Industrial internet; Simulation	Mechanical engineering (rail supply industry)	SME	Project of production processes digitization and simulation using FlexSim software
Quinn[72]	Additive manufacturing	Automotive industry	Large	Application of AM in General Motors Corporation to produce lightweight versions of structural components as a mean to meet fuel-economy regulations and achieve longer ranges of electric car versions

(Continues)

TABLE 3 (Continued)

Source, year	Main I4.0 technologies	Industry sector	Industry size	Main topics
Garcia-Muina et al.[73]	Industrial internet	Mechanical engineering (machinery)	Large	Digitization of production processes to allow companies to shift from linear to the circular economy
Grieco et al.[74]	Big Data & Analytics	Textiles, fashion and creative industries	Large	Definition of a decision support system to support users in making better decisions about the organization of the objectives (from the suppliers to the customers)
Kuo et al.[75]	Advanced manufacturing solutions	Mechanical engineering (machinery)	SME	A novel approach to predict the work status of machines using inexpensive sensors for data collection
Lima et al.[76]	Augmented reality	Automotive industry	Large	Definition of an application to indicate the location of 3D coordinates in a given environment, applied in Volkswagen Group
Lin and Kumar[77]	Industrial internet	Mechanical engineering (rail supply industry)	SME/Large	Development of an intelligent cloud with hybrid cloud learning and collaborative management to optimize railway maintenance
Manufacturing Tomorrow[78]	Big Data & Analytics	Automotive industry	Large	Development of a scalable platform by AUDI AG based on big data to improve the quality control process for the welds in its vehicles
Marilungo et al.[79]	Industrial internet	Mechanical engineering (machinery)	SME	Application of ICT and IoT technologies to optimize the production in terms of energy efficiency increase
MindSphere, Siemens Software[80]	Industrial internet	Aeronautics industry	Large	Development of an IoT platform, called MindSphere, by Siemens AG and applied in the major UK airports to allow companies to connect via cloud to the platform and use data generated from the products
Mourtzis et al.[81]	Augmented reality	Mechanical engineering (machinery)	SME	Development of a mobile application to visualize CAD instruction for bending processes
Oliff and Liu[82]	Big Data & Analytics	Electric and Electronic Engineering Industries	SME	Integration of data-mining principles into existing manufacturing processes to improving process and product quality
Rail Cargo Group[83]	Augmented reality; Industrial internet	Mechanical engineering (rail supply industry)	Large	Development of the platform SPACE1 merging AR, industrial internet, and artificial intelligence to reduce risks for operators during the routine inspections on cargo trains
Rosi et al.[84]	Augmented reality	Mechanical engineering (machinery)	SME	Development of an application to enhance the safety of employees when performing troubleshooting tasks
Sanz et al.[85]	Industrial internet	Automotive industry	Large	Combination of industrial internet and artificial intelligence to introduce predictive maintenance in SEAT automotive paint shop process
Schumacher et al.[86]	Advanced manufacturing solutions; Industrial internet	Aeronautics industry	SME	Proposal and company-application of an Industry 4.0 maturity model mainly focusing on evaluating advanced manufacturing solutions and real-time connectivity status

(Continues)

TABLE 3 (Continued)

Source, year	Main I4.0 technologies	Industry sector	Industry size	Main topics
Shahzad and O'Nils[87]	Industrial internet	Mechanical engineering (machinery)	SME	Development of an IoT-based condition monitoring system to determine the defects and performance degradation of machines
Siemens[88]	Additive manufacturing; Industrial internet	Mechanical engineering (rail supply industry)	Large	Development of the Rail Service Center using AM to produce plastic parts while the Automated Vehicle Inspection allows trains to enter the workshop and automatically undergo inspections
STELIA Aerospace[89]	Additive manufacturing	Aeronautics industry	Large	Application of AM in STELIA to develop 1 sq. Meter plane fuselage, eliminating the current used stiffeners
Strandhagen et al.[90]	Advanced manufacturing solutions; Industrial internet	Maritime industries	SME	Introduction in the company of collaborative robots and launch of a project of production processes digitization
	Additive manufacturing; Industrial internet	Mechanical engineering (machinery)	Large	Introduction in the company of 3D printing to reduce complexity and use of Industrial internet to increase the percentage of automated processes
	Advanced manufacturing solutions; Industrial internet	Mechanical engineering (machinery)	Large	Introduction in the company of collaborative robots and launch of a project of production processes digitization
	Advanced manufacturing solutions; Industrial internet	Mechanical engineering (machinery)	Large	Introduction in the company of collaborative robots and launch of a project of production processes digitization
Szirányi[91]	Advanced manufacturing solutions; Industrial internet	Automotive industry	Large	Development and implementation of a complex IT platform able to manage manufacturing operations using digital sensors and collaborative robots
Ultimaker[92]	Additive manufacturing	Automotive industry	Large	Application of AM in Volkswagen AG to produce tooling, jigs, and fixtures
van Lopik et al.[93]	Augmented reality	Electric and Electronic Engineering Industries	SME	Development of an Augmented Repair Training Application, i.e., an interface to support non-AR expert end-users without the need for expertise in programming and that are flexible to changing processes
Vorraber et al.[94]	Augmented reality; Industrial internet	Automotive industry	Large	Integration of IoT and AR using Microsoft HoloLens and an audio-only communication system for remote maintenance
Weiss et al.[95]	Advanced manufacturing solutions	Automotive industry	Large	Application of industrial robots for human-robot collaboration in an automotive assembly line

3 | INDUSTRIAL APPLICATIONS DESCRIPTION

In this Section, the industry-oriented articles presented in Table 3 are classified and discussed according to the enabling technology/technologies they apply. The absence of sections devoted to some specific enabling technology is due, to the Authors' knowledge, to the lack of publications of case studies involving that technology.

3.1 | Advanced manufacturing solutions—Enabling technology ID. #1

Concerning the implementation cases of the first I4.0 enabling technology in industry, Weiss et al.[95] presented three case studies about the use of industrial robot prototypes for human-robot collaboration. Such interaction was tested in an automotive assembly line. Results from the use experiences show that robotic systems are still limited

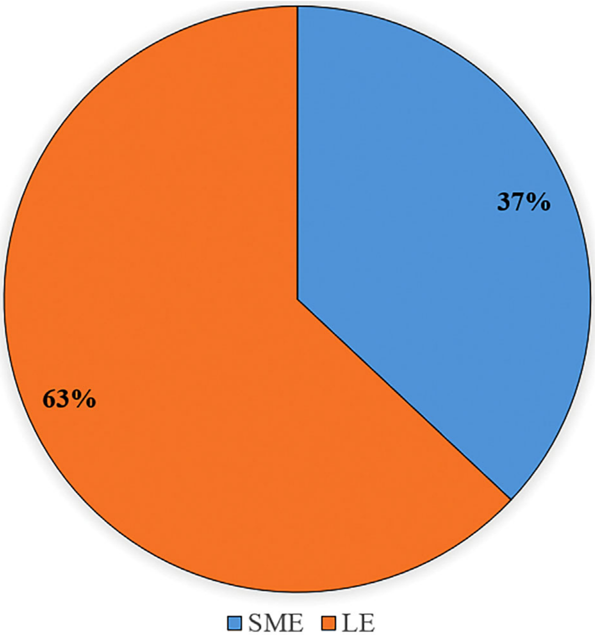

FIGURE 2 Size of the industrial companies involved in I4.0 projects.

in terms of acceptance and usability. The operators complain about the touch panel used to control the robot because it creates a further layer between them, the robot and the product to work, causing a productivity decrease. Moreover, the operators continuously express the fear of being replaced by the robotic system causing further skepticism and rigidity. Cohen et al.[70] and Bortolini et al.[3] defined a general architecture to introduce I4.0 technologies into existing assembly systems. The Authors proposed to install sensors (1) on the operators to track their presence and to map relevant data and information, (2) on the products to track data as size, dimensions, and tasks to perform, for example, work cycle, and, finally, (3) on the assembly station to map the state of the actuators, the availability of the station and the presence of the product/operator. This intelligent network allows a real-time data exchange among all the smart factory components getting better performances in terms of cycle time, productivity, and human operator ergonomics. The proposed architecture was implemented in an Italian SME producing industrial refrigerators getting low training time, high ergonomic and safety levels when performing the assembly tasks as well as 35% increase of the productivity. Kuo et al.[75] introduced a novel approach to predicting machines' work status using inexpensive sensors for data collection. To validate their approach, the Authors used it in a real industrial machine of a manufacturing company located in Taiwan.

3.2 | Additive manufacturing—Enabling technology ID. #2

Regarding the implementation of AM in industry, a top-class example is given by General Motors Corporation (GM).[72] AM helped the company to produce lightweight versions of several structural components, and reducing weight is crucial to meet fuel-economy regulations and to achieve longer ranges of electric car versions. Moreover, AM guarantees more flexibility to make unique designs simulating the input parameters of the components before printing. Finally, AM offers relevant opportunities for material usage, that is, GM needs to focus on steel and aluminum to meet its specific needs. BMW reported on its website that also that the company counts several successful experiences in implementing printed metal components to their cars. As a reference example, the company chose to use AM to manufacture two parts of its i8 Roadster, that is, the convertible's roof bracket and

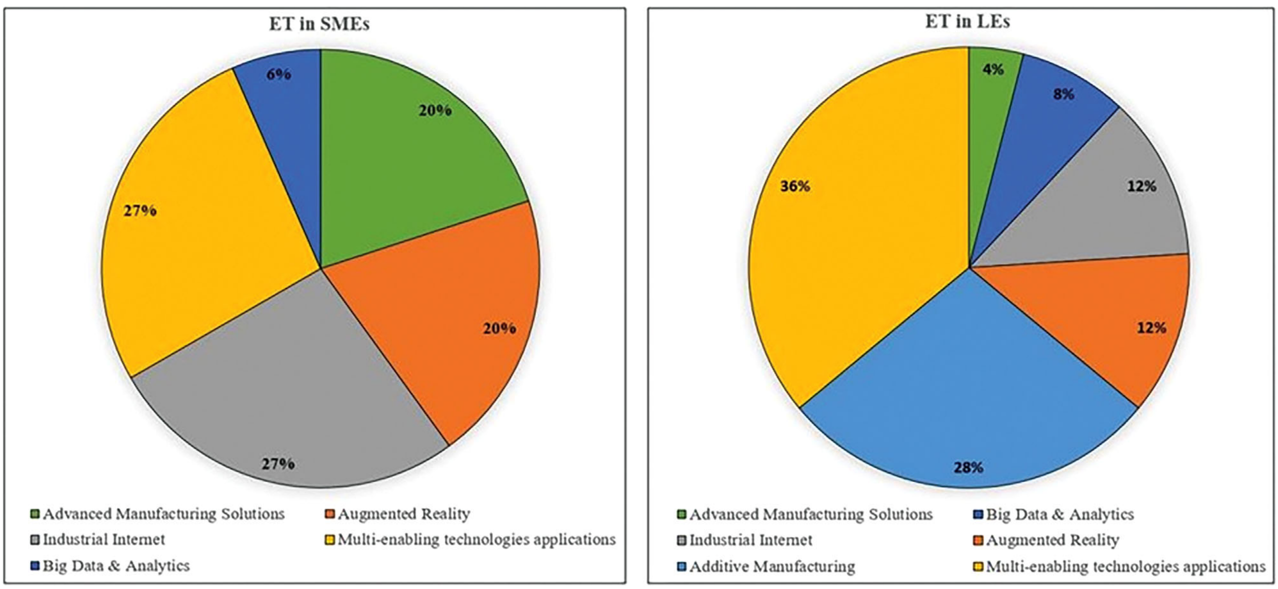

FIGURE 3 I4.0 enabling technology use in SMEs and large enterprises.

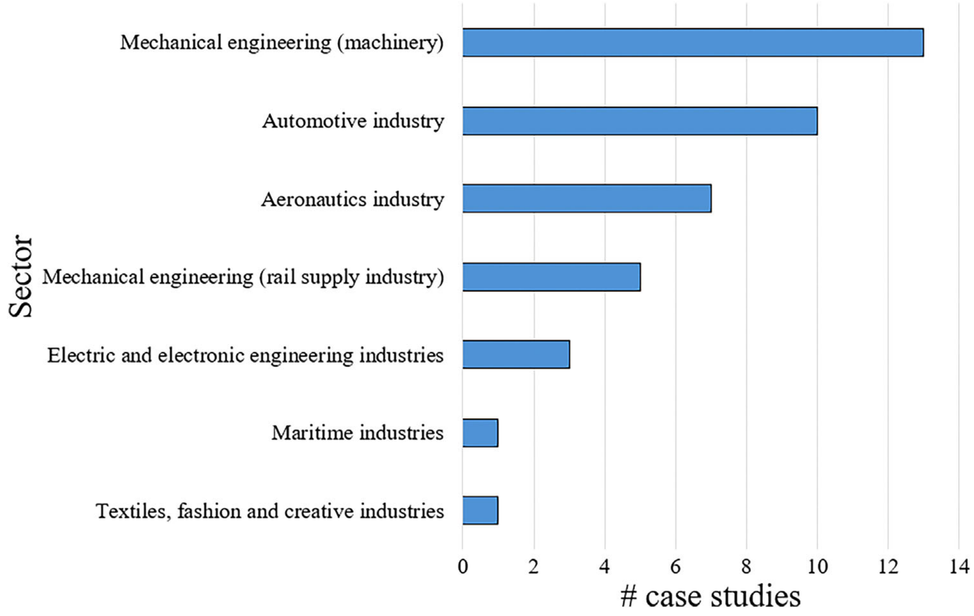

FIGURE 4 Case studies: industrial sector segmentation.

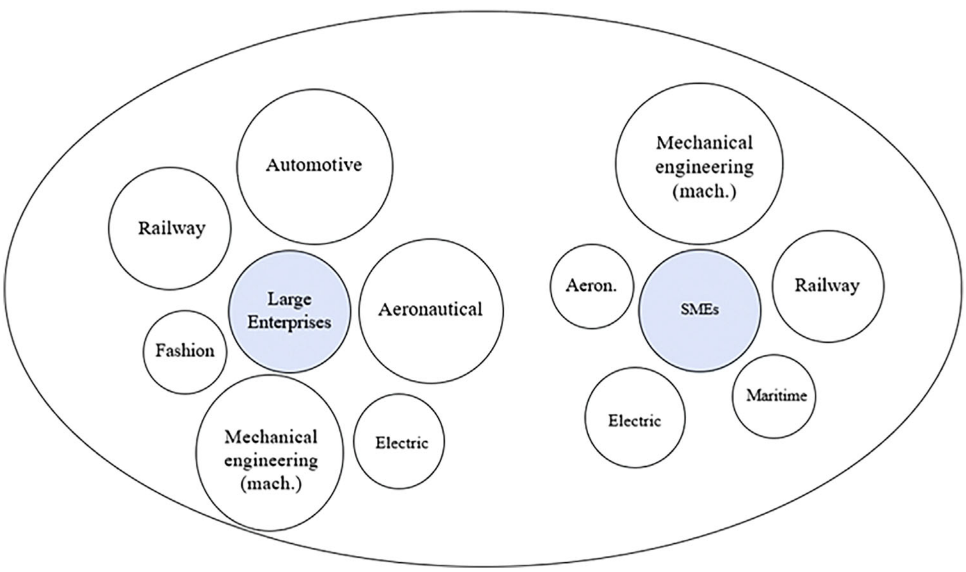

FIGURE 5 Industrial applications of I4.0 enablers: industrial sector and company size segmentation.

the window guide rail produced in a quantity of 100 units per day.[66] A further example from the automotive sector is by Volkswagen AG, a top company for 3D printing: the main use of AM in the company is for applications like tooling, jigs and fixtures. Almost all of its tooling production is based on 3D printing, leading to relevant economic savings.[92] AM offers valid opportunities for implementation also in the aeronautics industry because it allows reducing the global aircraft weight by using innovative materials such as titanium and nickel-based alloys. In 2018, the French aerospace company STELIA developed a 1 m^2 plane fuselage demonstrator with 3D printing technology, which should eliminate the currently used stiffened attached to the fuselage panels with fixing screws and welding.[89] Other relevant implementation cases can be found in Castor,[69] involving Boeing, Airbus and NASA. The American company Boeing replaced multiple parts in large assembly used to produce the antenna with a single 3D printed component, reducing the weight of the antenna and the production time. Boeing used AM for the production of its jets, allowing the reduction of the engine's weight and making Boeing 777x the most efficient twin-engine jet in the world, decreasing the fuel consumption and the operative costs. Moreover, Airbus installed the first titanium parts produced through 3D printing for a serial production aircraft. A relevant example is the Airbus A350 XWB, which has more than 1000 3D printed components. Finally, NASA is deploying AM for space exploration: with 7000 pounds of spare parts sent to the International Space Station every year, it is trying to lighten the load and to reduce the costs by using 3D printing.

3.3 | Augmented reality—Enabling technology ID. #3

This sub-section describes the most relevant applications of AR in industry. Mourtzis et al.[81] developed a mobile application to visualize Computer Aided Manufacturing (CAD) instructions for bending processes using AR. The application relies on high usable menus and advanced visualization, including indications, text instructions, and safety zones for the operators. The developed technology was applied to a bending machine of a CNC manufacturing industry, proving its benefits in supporting the training process of inexperienced workers in using the new manufacturing machine speeding up the learning process for technicians. Van Lopik et al.[93] developed an Augmented Repair Training Application (ARTA), conceived as an interface to support non-AR expert end-users (e.g., shop floor) without the need of content libraries, expertise in programming and that are flexible to changing processes. The main element of innovation of the method proposed in this study was to capturing tacit and explicit knowledge from experts by using eye-tracking technologies combined to information mapping to provide instructions to an AR-based device. The technology-testing phase was in a European SME in the Used and Waste Electronic and Electrical Equipment sector (UEEE/WEEE), moving toward the adoption of I4.0, to support knowledge sharing between expert and novice workers for a phone repair task. Results from implementing the ARTA method to create AR content were partially satisfactory. When implementing the method in the SME, the real-world case revealed more complexity than expected due to the unfamiliar of the industrial participants to 3D environments, eye tracking technologies and innovation of the device. Researchers were required to assist the industrial practitioners in the implementation process and recover from unexpected errors, while, globally, stakeholders evaluated the training tool as a success. In the automotive sector, Lima et al.[76] defined an AR application to indicate the location of 3D coordinates in a given environment, which can be applied to many different applications in cars, for example, maintenance assistant, intelligent manual. The system was applied to the Volkswagen AG, getting satisfying results. Bysko et al.[68] proposed an innovative paint shop concept on behalf of a German car manufacturer. The idea behind the research is to reduce the bottleneck in the car paint shop, caused by frequent changeovers of the painting guns, through a new type of sequencing problem studied from an algorithmic and practical perspective. The new problem allows real-time car sequencing through the installation of buffers to consider dynamic changes. In the aeronautics industry, Airbus launched the iflyA380 app based on AR to enhance passengers' experience.[63] By using the app, the travellers can book a flight, interact with the aircraft through AR and take a 360° tour of the cabin ahead of time.

3.4 | Industrial internet—Enabling technology ID. #6

Among the most relevant applications of the industrial internet technology in industry, Garcia-Muina et al.[73] developed a procedure based on the digitization of the production processes to implement the impact assessment tools, for example, Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and S-LCA (Social—Life Cycle Assessment), and on business intelligence systems to provide appropriate sustainability performance indicators for the definition of the new Circular Business Model. The proposed procedure was tested and validated in a large Italian company producing ceramic tiles, which experienced benefits in shifting from a linear to a circular economy. Siemens AG is a relevant example of a company making huge use of Industrial IoT (IIoT). The company developed an industrial cloud platform called MindSphere, in which open architecture, open ecosystem and open application programming interfaces allow manufacturing companies to connect via cloud platform and to use the data generated from IIoT products. In this way, by putting technology in place, the company will gain rapid access to proactive and reactive analytics in its plant to understand where improvements are needed, making possible to see the future changes virtually before realizing them. Siemens AG implemented such technology in a major UK airport, experiencing lost or delayed baggages, providing rapid benefits and improvements.[80] Sanz et al.[85] performed a study in the automotive sector combining AI and industrial internet to introduce predictive maintenance in the automotive paint shop process of the car manufacturer SEAT, in Spain. By implementing such technologies, employees experienced time savings and the increase of their process efficiency. Recently, the industrial internet technology is finding full application in the railway industry. The big challenge of the railway maintenance is to generate knowledge from data and information. This feeling generated the IN2CLOUD project,[77] aiming at building an intelligent cloud with hybrid cloud learning and collaborative management to allow companies to learn from each other. Moreover, IN2CLOUD will help the transition of railway industry system from local to global optimization in a collaborative way through information sharing.

3.5 | Big data & analytics—Enabling technology ID. #9

This sub-section discusses the applications involving big data & analytics technology. Grieco et al.[74] proposed a decision support system (DSS) designed to support the users, that is, industrial practitioners, to take better decisions on the organization of the objectives throughout the complex Bottega Veneta supply chain, a large Italian company in the fashion industry. The developed DSS covers the external raw material suppliers, the internal production job-shops, and the local subcontractors. Specifically, it provides a graphical representation of the production orders based on the complex links among the different tasks. Furthermore, it produces reports on the resources to analyze and plan, in terms of usage and efficiency, and reports providing insight into the capacity of the plan to satisfy the required due dates. In the automotive sector, to achieve an I4.0 level of production and to become a smart factory, AUDI AG needs to develop a scalable and flexible platform to embrace the transformative power of advanced digital technologies such as big data & analytics and edge computing. As reported by ManufacturingTomorrow,[78] AUDI AG collaborated with Intel and Nebbiolo on a proof of concept to improve the quality control process for the welds in its vehicles. To this aim, they created algorithms using Intel's Industrial Edge Insight software and Nebbiolo Edge platform for streaming analytics that resulted in predictive analytics and modelling to transform factory data into valuable insights.

3.6 | Case studies on multiple enabling technologies

This sub-section presents the I4.0 implementation projects concerning the application of a joint set of enabling technologies. Strandhagen et al.[90] explored the fit of I4.0 applications with manufacturing logistics through multiple industrial case studies involving four Norwegian manufacturing companies. The first examined company is Kleven Maritime AS including platform supply vessels, construction vessels, seismic vessels, and anchor-handling vessels. The most relevant improvement areas for the company are the standardization of products and components to best manage the increasing product variety and the reduction of throughput times. Kleven Maritime AS states that higher level of automation, the implementation of collaborative robots, and the digitization of production processes are the most relevant categories of I4.0 applications in manufacturing logistics. As key result of this study, cobots are now used to perform welding operations previously executed manually. Brunvoll AS produces thruster systems for maneuvering and propulsion of several different types of advanced vessels. The company considers I4.0 as a relevant opportunity to increase competitiveness while it considers less relevant its impact on manufacturing logistics. The improvement areas for the company are the optimization of the material flow, and the reduction of the throughput time of raw materials and finished goods. 3D printing is among the I4.0 technologies that the company started to implement to reduce complexity, as well as the use of the industrial internet to increase the percentage of automated processes. Ekornes AS is a furniture production company with a strong focus on product customization. The company considers I4.0 a strategic asset to increase the efficiency of the material flow by reducing the throughput time and increasing the ICT utilization. Ekornes AS expects that the level of automation, the introduction of collaborative robots and the digitization of production processes will increase in the next few years even if, so far, they are at a very early stage of implementation. Finally, Pipelife is a European leading producer of plastic pipes. The company sees I4.0 as a realistic goal, expected to improve manufacturing logistics significantly, and it is largely investigating possible applications to increase efficiency of inbound logistics, to improve the material flow, to increase ICT use, to reduce setup times and to reduce the stock of raw materials and finished goods. Technologies as 3D printing are not considered relevant to Pipelife, while the automation and digitization of production processes are expected to increase within the next few years. This study reveals that the four manufacturing companies are at a very early stage of implementation of the I4.0 technologies. In particular, they foresee the potential but, at the same time, are skeptic about the rapid investment and introduction of these new technologies within their industrial settings. Dalenogare and Ayala[50] performed a survey in 92 Brazilian manufacturing companies to explore the implementation level of the I4.0 enabling technologies. The main findings of this study showed that I4.0 is related to a systemic adoption of the so-called front-end technologies, that is, smart manufacturing, while ICT-oriented technologies, for example, big data & analytics, are still poorly implemented in the sample under examination. In the railway sector, the company Rail Cargo Group adopted the platform SPACE1, which merges AR, industrial internet and AI to reduce risks for operators during the routine inspections on cargo trains. The proposed solution allowed the operators to perform the cargo inspections hands-free, simplifying the managing process and sharing know-how.[83] Another relevant area of investigation, which merges multiple I4.0 enabling technologies, is the train maintenance. As reported on the Siemens AG website in 2021, the company opened the Rail Service Center. The services offered by the center are completed paper-less. Besides, it uses 3D printers to produce plastic spare parts quickly and directly on site, while the Automated Vehicle Inspection (AVI) allows trains to enter the workshop and automatically undergo inspection of wheels, axles and tread patterns using the latest laser technologies. Thanks to predictive maintenance strategies, Siemens AG guarantees a target availability rate of about 99%.[88] Barbosa et al.[65] proposed to integrate cyber physical systems (CPSs) and Intelligent Products (IP), as an innovative method to investigate the different phases of the product life cycle. They illustrated such integration in Bombardier, that is, train manufacturer, and in Whirlpool, that is, washing machines producer, covering the product production and use phase. Bombardier initially explored the CPS concept and its benefits in the use phase of a train to increase the quality of its health status monitoring and diagnosis. In parallel, Whirlpool was involved in the EU FP7 GRACE (Integration of process and quality control using multi-agent technology) project, in which the notion of IP was combined to CPS to improve the production efficiency and the product quality, considering the use of multi-agent technology and joining the process and quality control. A Whirlpool's laundry washing machine production line was used as demonstrator, proving relevant benefits in terms of online adjustments of the process parameters, early detection of quality errors and customization of the final washing machine. In the automotive sector, KPMG supported the Italian Automobili Lamborghini S.p.A. in developing and implementing a complex ICT platform able to manage manufacturing operations, allowing the company to feature a novel modular design, using digital sensors and collaborative robots.[91]

3.7 | Key outcomes and discussion

To sum up the main results coming from this analysis, while most of the existing papers published on I4.0 are literature reviews or theoretical analysis, just a few assess and analyze the implementation of I4.0 enabling technologies in industrial companies. Globally, most of the collected applications involves large enterprises in the transport sectors, that is, automotive, aeronautical, and railway, and deals with ambitious projects using a set of enabling technologies. SMEs involved in I4.0 projects usually belong to the mechanical engineering sector and the innovation projects deal with a preliminary feasibility analysis of introducing a specific enabling technology in their industrial settings. In many of the analyses cases, while the top management was thrilled about the starting of such projects, the line operators were sceptical because from one side they were afraid of not knowing how to use such new technologies and, from the other side, they were afraid of being replaced soon. Main results from this study are quite in accordance with that coming from other studies performing statistical analysis on the penetration level of I4.0 technologies. As reference example, the study of Michna and Kruszewska[97] performed statistical analysis on a panel of about 125 worldwide industrial participants, highlighting that AM is much more often used, together with AR, simulation, big data & analytics, integration of horizontal and vertical systems and cloud computing. Detailed results of the statistical analysis, in terms of mean, median, mode, and standard deviation can be found in the paper.

Moreover, the research carried out on both academic databases and company online information highlights that implementation cases of I4.0 technologies in industrial companies often arise from collaborations between companies and public stakeholders, for example, Universities, research entities, competence centers and business schools as well as private consulting companies. This aspect marks that the I4.0 plan is still at the beginning of its path and that companies are not yet able to implement such innovation projects in complete autonomy, but they need to be supported in such a transition. In this context, focusing on the role covered by competence centers and considering the reference case of Italy, their establishment represents a far-sighted government project of strategic support for companies to face the challenges led by the fourth industrial revolution. The decree of the Ministry of Economic Development of 29/1/2018, defining the conditions, criteria and methods of financing, paved the way for the selection of eight highly specialized competence centers on I4.0 issues. The investment in training and expertise, in which Italy still faces a gap with other European countries, is at the basis of this policy which aims to be a concrete support in strengthening the competitiveness of the companies in terms of innovation and research. The main goals of the competence centers are (1) to counteract the strong fragmentation and dispersion of the technology transfer centers, (2) to follow the European examples as Catapult centers (UK), Poles d'Innovation (France), and Fraunhofer (Germany), (3) to enhance the existing realities starting from the Universities of excellence according to a clear logic of specialization on the technologies of the Business Plan 4.0, (4) to intensify University-business relationships through the establishment of joint partnerships according to a sustainable planning from an economic and financial point of view, (5) to give visibility to these initiatives with an unprecedented form of funding, promoting their complete placement within the European framework. On the other hand, several I4.0 maturity models were developed to help companies assess their capabilities and degree of adoption of the essential I4.0 enablers and help them develop an incremental implementation strategy and a plan. One of the better maturity models is the Smart Industry Readiness Index (SIRI) developed in 2017 by the Singapore Economic Development Board (EDB) in collaboration with a network of companies and academic members. SIRI includes tools and frameworks to support manufacturers to start, scale and maintain their digital manufacturing transformation, covering the dimensions of people, technology, and organization. To date, more than 200 assessments have been performed for companies in Singapore and abroad (67% large enterprises and 33% SMEs) involving 12 manufacturing industries and 14 countries. Although SIRI needs to increase the panel of partner companies and investigate other industrial sectors, in more countries, the index is consistent and contributed to the development of other maturity indices, which are crucial to support and sustain companies in the transition toward the fourth industrial revolution.

4 | SUMMARY AND CONCLUSIONS

The concept of Industry 4.0 (I4.0) emerged in 2011 as the fourth industrial revolution to drive industry toward a digital era. In this field, most of the papers found in the literature present surveys on the topic, exploring the presence of links and synergies between the fourth industrial revolution and specific manufacturing and operations management areas and its impact on a set of key system performance indicators. However, the current implementation level of I4.0 technologies in multi-sector real-sized industrial companies remains largely unexplored. A structured survey of forty (40) I4.0 technology use cases, applied in both SMEs and large enterprises of different industrial sectors, was conducted to address this gap. The analysis is performed using academic databases and specific companies' published information to collect relevant implementation cases and draw a global picture. The main findings show that 63% of the identified applications involves large enterprises, especially in the transport sector, that is, automotive, aeronautical, and railway, and deal with ambitious I4.0 projects focused on implementing a set of the enabling technologies, that is, primarily advanced manufacturing solutions, AM, and the industrial internet. SMEs involved in I4.0 projects primarily belong to the mechanical engineering sector and the related projects, representing the 37% of the total, represent preliminary feasibility studies for introducing a specific enabling technology. The presented study reveals that, among the set of enabling technologies, advanced manufacturing solutions, AM, AR, and the industrial internet appear to be the most promising ones, primarily adopted by SMEs and large enterprises. The findings of this study can support companies looking for technological progress because they can benefit from a clear overview of the I4.0 technologies and the experience with actual industrial implementations in different companies and sectors. Moreover, this paper is also valuable for the

TABLE 4 Open research questions to drive future research.

Research questions
1. In the modern industrial environment, do industrial companies have a clear view of the Industry 4.0 principles, and the potential benefits derived from the implementation of its enabling technologies?
2. How to attract and support small, medium and large industrial companies implementation of Industry 4.0 enabling technologies, help them assess their maturity level and reduce the implementation challenges?
3. What role should Universities and research institutions play to support industrial companies in such a transition?
4. Have Nations defined proper development plans and incentives for industrial companies to invest in Industry 4.0 projects?
5. How to reduce the line operators' skepticism and resistance toward the introduction and use of these new technologies?
6. What are the Industry 4.0 enabling technologies that should be implemented as a priority?

scientific community because it can support researchers in identifying the industrial sectors most involved in I4.0 implementation projects and those still at the beginning of their transition. In accordance with these results and considerations, Table 4 provides a future research agenda, highlighting relevant open research questions to drive and support the implementation of Industry 4.0 technologies in manufacturing companies.

Answering these questions will be a first goal to expand the knowledge of Industry 4.0 within industrial companies and support industry and practitioners toward the implementation of Industry 4.0 principles. Further research questions need to be outlined to extend the Industry 4.0 research in other areas, issues, and industries.

DATA AVAILABILITY STATEMENT

Data sharing not applicable—no new data generated.

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