Industry's 4.0 transformational process:

how to start, where to aim, what to be aware of

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Abstract

Industry 4.0 has fused digitalisation with traditional industrial processes bridging the physical and virtual worlds and opening unimagined possibilities for 21st century business growth. Research is still evolving toward the development of frameworks linking Industry's 4.0 enabling technologies to specific goals and to their impact on the manufacturers' businesses.

A systematic review of all peer-reviewed managerial research is performed to extract Industry's 4.0 enabling technologies, barriers and goals. A framework linking technologies, barriers, and goals is then developed together with a web application based on its contents. The use of the framework is demonstrated through its application to two specific empirical case studies.

The review shows that there are 9 classes of Industry's 4.0 enabling technologies, whose different arrangements lead to the achievement of up to 15 business goals that can be thwarted by 21 barriers. The pursuit of these goals leads to three different destinations, i.e., three diverse digital transformations of the manufacturing firms. This paper provides a holistic framework that analyses the relationships among Industry's 4.0 enabling technologies, barriers and goals. It appeals to managers who can use its contents along with the web application to derive recommendations and suggestions tailored to their Industry's 4.0 journeys.

Keywords: Industry 4.0, digital transformation, manufacturing, framework, journey.

Introduction

The term Industry 4.0 has been introduced for the first time at the 2011 Hannover fair and has made its first official appearance in literature in 2013 as a project launched by the German government to promote the renovation of the country's factories (Zangiacomi et al. 2020; Xu and Duan 2019; Xu, Xu, and Li 2018; Kagermann et al. 2013). Industry 4.0 is a new industrial transformation that aims to connect people and things 'anytime, anyplace, with anything and anyone, ideally using any path/network and any service' (Wagner et al. 2017). Smart mobility, logistics, buildings, products, grids are different applications of Industry 4.0, although smart factories are its focal point (Osterrieder, Budde, and Friedli 2020; Schwab 2016). The logic behind smart factories aims to transform industrial production from a nuts-and-bolts process to an integrated cyber-physical production system (Liao et al. 2017; Wagner et al. 2017).

From a conceptual standpoint, Industry 4.0 is a transformative journey in which changes can be both evolutionary and revolutionary (Calabrese, Levialdi Ghiron, and Tiburzi 2020; Wagire et al. 2020; Kayikci et al. 2020). On the one hand, changes can be evolutionary because some of Industry's 4.0 enabling technologies, such as sensors and robots, are the result of a long-wave innovation that began with the Third Industrial Revolution (Reischauer 2018). On the other hand, Industry 4.0 can be a revolutionary journey because it can affect manufacturers' core business, shifting it from making and selling products to providing solutions (Strozzi et al. 2017). At any rate, Industry 4.0 is a transformation enabled by a series of technologies which provide new and improved approaches to value creation, proposition, and capture (e.g. enhanced productivity, better quality products, better working conditions, sustainability, development of innovative capabilities and new revenue models) (Chiarini, Belvedere, and Grando 2020; Bibby and Dehe 2018; Lu 2017; Tsolakis et al. 2020).

Up to recently, research has contributed mainly to the technical side of Industry 4.0 (Büchi, Cugno, and Castagnoli 2020; Osterrieder, Budde, and Friedli 2020). Managerial studies have focused on theoretical investigations of Industry's 4.0 ontology (Kusiak 2018; Yin et al. 2018); on its link with other practices such as sustainability (Machado, Winroth, and Ribeiro da Silva 2019; de Sousa Jabbour et al. 2018), circular economy (Rosa et al. 2020) and lean manufacturing (Rosin et al. 2020; Buer et al. 2018); and on some of its challenges (e.g. migration paths for implementation and business models innovation) (Schneider 2018; Jardim-Goncalves et al. 2017).

Studies sustaining managers who are piloting their factories through the Industry's 4.0 transformative journey are still scarce (Culot et al. 2020; Chiarini, Belvedere, and Grando 2020; Wagire et al. 2020). Previous studies on this topic from either peer-reviewed or grey literature have moved in three main directions. First, they have elaborated frameworks to categorize the major Industry's 4.0 enabling technologies, thus sustaining managers in understanding the factory areas (production line, warehouse, etc.) affected by each technology (Culot et al. 2020; Frank, Dalenogare, and Ayala 2019; Rüßmann et al. 2015). Second, they have developed assessment models to support firms in evaluating their progress in the adoption of the main Industry's 4.0 enablers and in tackling its primary barriers (Wagire et al. 2020; Pacchini et al. 2019; Bibby and Dehe 2018; Geissbauer, Vedso, and Schrauf 2016; Lichtblau et al. 2016). Third, they have analysed the benefits and business model's changes of specific enablers, such as blockchain, artificial intelligence, and additive manufacturing technologies (Zhang and Chen 2020; Lu 2019; Viriyasitavat et al. 2018).

A holistic framework is still missing to aid managers in choosing the right combinations of Industry's 4.0 enabling technologies to reach specific goals and to warn them against the most relevant barriers (Raj et al. 2020; Wagire et al. 2020; Schneider 2018). This study develops one such framework. Through a systematic literature review, this paper identifies and categorizes the primary Industry's 4.0 enablers, goals, and barriers. Subsequently, a framework linking these elements is built (Culot et al. 2020). The proposed framework is used as a theoretical foundation to design and deliver a web application aiding manager in their Industry 4.0 journey. Such a web application is an innovation in managerial research aiming to facilitate the industrial use of academic research.

The next section presents the method that has been adopted to carry out the systematic literature review. The following sections explain the elements of the framework and their relationships. Afterward, the framework is built and discussed, and the web application is introduced by means of two empirical cases. Finally, the implications of the research are discussed.

Research Methodology

Research Design

Although Industry 4.0 is still in its early stages (Buer et al 2018), the topic has received a great deal of attention from scholars, practitioners, and governments resulting in a rapid rise in the number of related publications (Wagire, Rathore, and Jain 2020). Along with these, a number of literature reviews have been published. Some of the topics addressed by previous reviews are: the analysis of Industry's 4.0 research trends and future directions (Sony, Antony, and Douglas 2020; Wagire, Rathore, and Jain 2020; Erro-Garcés 2019); the identification of the critical factors for its implementation (Szász et al. 2020; Sony and Naik 2019); the analysis of its many definitions (Culot et al. 2020; Nosalska et al. 2019); the discussion of its links with sustainability and the circular economy (Kerin and Pham 2020; Ren et al. 2019); and the investigation of its role in changing manufacturing practices (Kuo and Kusiak 2019; Ben-Daya, Hassini, and Bahroun 2019).

This review develops a framework to assist managers in reaching the goals untapped by the Industry's 4.0 transformation. To date, the lack of such kind of research represents one of the obstacles preventing the spreading of this paradigm (Culot et al. 2020; Wagire et al. 2020; Erro-Garcés 2019). In particular, the framework's purpose is to link Industry's 4.0 enabling technologies to goals that can be achieved by adopting these technologies and to barriers that can prevent such achievements.

The framework is developed by content analysing a sample of papers collected through a systematic literature review. The whole process follows a three-phase methodology to guarantee an unbiased, reproducible, and transparent collection and analysis of all the relevant papers (Sony and Naik 2019; Tranfield, Denyer, and Smart 2003; Greenhalgh 2997). In the first phase, *planning*, the research objective, i.e. the purpose of developing a framework linking Industry's 4.0 enabling technologies, goals and barriers, has been set forth. In the second phase, *executing*, relevant papers have been collected and analysed through a rigorous procedure explained in the next section. In this phase, the Industry's 4.0 enabling technologies, barriers, and goals, as well as their relationships, have been extracted from research papers by means of content analysis and the framework has been built. Finally, in the third phase, *reporting*, a web application based on the contents of the framework has been developed and applied to the analysis of the Industry's 4.0 transformative journey of two manufacturers. Figure 1 provides a summary of the research structure.

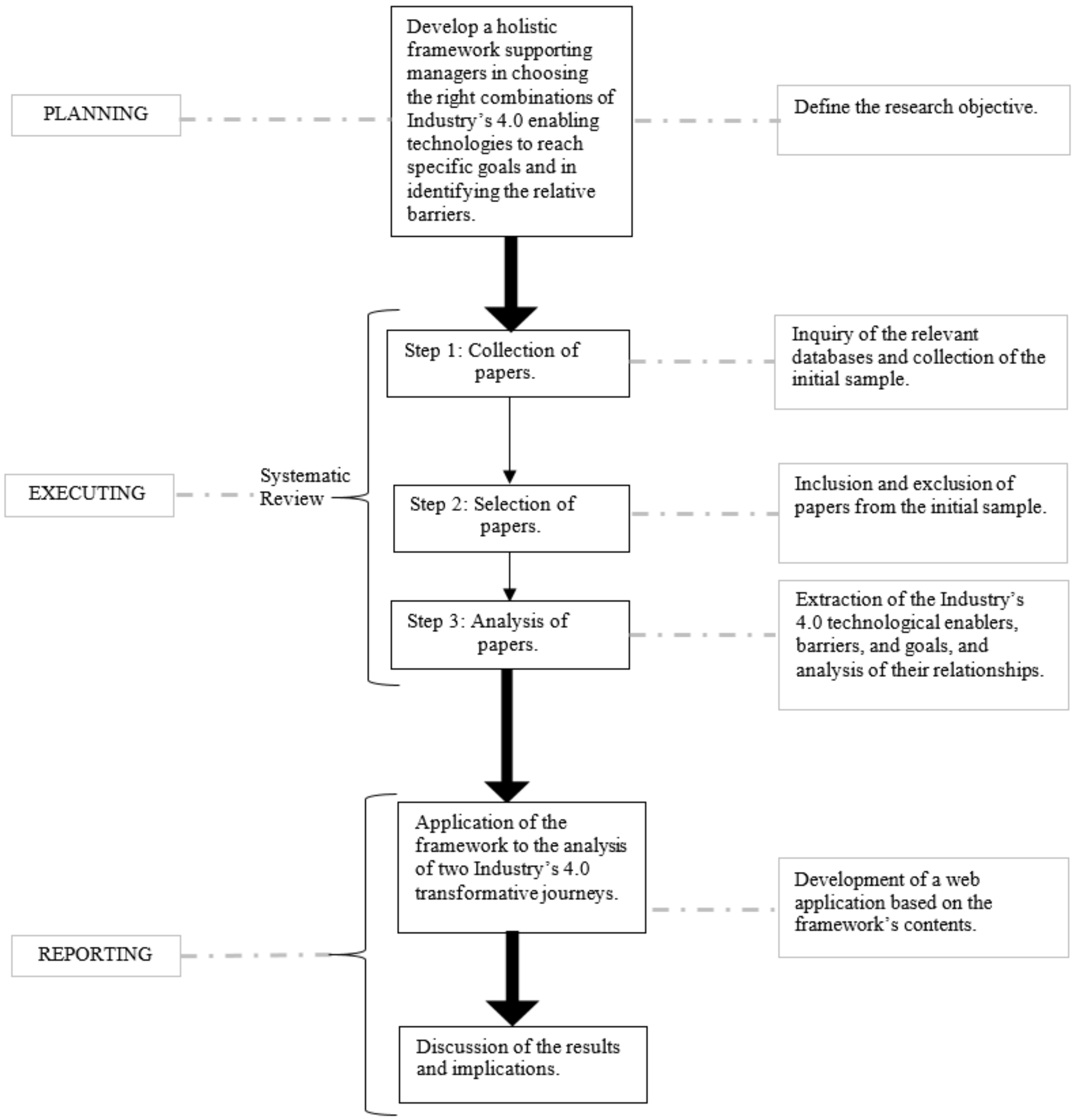


Figure 1 – Research design

Analysis of the Literature

Step 1: Collection of papers

The collection of the papers has been carried out via Scopus, the best source of information on a wide range of topics, including Industry 4.0 (Kipper et al. 2020). Grey literature has been excluded from the systematic collection as done in analogous literature reviews (Calabrese, Levialdi Ghiron, and Tiburzi 2020; Sony and Naik 2019). The query consisted of a series of Industry's 4.0 synonyms taken from the study of

Schneider (2018) (see Table 1). The query retrieved 799 documents, which have been carried on to the second step for the inclusion/exclusion of the relevant ones.

Step 2: Selection of the papers

Out of the 799 peer-reviewed articles, those whose sources are not included in the Academic Journal Guide (AJG) list edited by the Chartered Association of Business Schools [GB] (2018) have been discarded (416). The AJG list has been chosen because it provides a 'guide to the range and quality of [peer-reviewed] journals in which business and management academics publish' (Calabrese, Levialdi Ghiron, and Tiburzi 2020).

At this point, 383 papers remained to be evaluated. Two of the authors recursively read the papers' titles and abstracts to select those to be included (Green et al 2017; Cassell and Symon 2004). According to Bryman (2015) and Tranfield, Denyer, and Smart (2003), this iterative, multi-personal reading reduces the intrinsic subjective bias inherent in this process. The authors adopted as inclusion criterion the retention of all articles whose title or abstract showed clear evidence of dealing with Industry's 4.0 enabling technologies, barriers, or goals, as well as their relationships. As a result of this process, 167 out of 383 papers have been included.

Table 1 presents a summary of the steps described so far, together with examples of the inclusion/exclusion process. As recommended by Denyer and Tranfield (2006) and Tranfield, Denyer, and Smart (2003), a list of all the papers included in each step has been reported in a supplementary file ('Supplementary material.xls'). This file also contains a list of the enabling technologies, barriers, and goals extracted from each paper (step 3).

Table 1 – Systematic collection and selection of the papers

Query Scopus: (799 results, June 2020)	TITLE-ABS-KEY ('factory of the future' OR 'smart factory' OR 'smart manufacturing' OR 'industrial internet' OR 'industry 4.0' OR 'industry 4.0') AND (LIMIT-TO (DOCTYPE , 'ar') OR LIMIT-TO (DOCTYPE, 'ip') OR LIMIT-TO (DOCTYPE , 're')) AND (LIMIT-TO (SUBJAREA , 'BUSI')) AND (LIMIT-TO (LANGUAGE, 'English')).
Articles not from ABS journals:	416
Articles not relevant:	216
Final Sample:	167
Examples of EXCLUSION:	

Wang Y., Zhang Y., Tao F., Chen T., Cheng Y., Yang S. 2019, Logistics-aware manufacturing service collaboration optimisation towards industrial internet platform, *International Journal of Production Research*, 57(12), 4007-4026, DOI: 10.1080/00207543.2018.1543967.	Excerpt from the *ABSTRACT*: '[T]his paper establishes an adjacent matrix-based logistics-aware MS collaboration optimisation (LA-MSCO) model with detailed definitions of time, cost and reliability attributes of logistics. An improved artificial bee colony algorithm with both dimensional self-adaptation and group leader mechanisms, i.e. DSA-GL-ABC, is proposed for solving the LA-MSCO problem.'
Versteyhe M., Debrouwere F. 2020, Application of non-deterministic uncertainty models to improve resource constraint optimal scheduling, *Journal of the Operational Research Society*, DOI: 10.1080/01605682.2020.1740622.	Excerpt from the *ABSTRACT*: 'Scheduling under non-deterministic uncertainty is a highly complicated problem. It is commonly known and observed that these type of projects can be late and over budget. It has been pointed out that the main reason is that the uncertainty is not, realistically, taken into account in any form of scheduling methods. We propose a modification of the common method for automated optimal scheduling under non-deterministic uncertainty by use of a realistic non-deterministic uncertainty model and by taking this explicitly into account in the optimization.'
Examples of INCLUSION:	
Arnold, C.; Kiel, D.; Voigt, K.I. 2016, How the Industrial Internet of Things changes Business Models in Different Manufacturing Industries, *International Journal of Innovation Management* 20(8), DOI: 10.1142/S1363919616400156.	Excerpt from the *TITLE*: 'How the Industrial Internet of Things changes Business Models in Different Manufacturing Industries'.
Müller J.M., Buliga O., Voigt K. I. 2018, Fortune favors the prepared: How SMEs approach business model innovations in Industry 4.0, *Technological Forecasting and Social Change*, 132(7) 2-17, DOI: 10.1016/j.techfore.2017.12.019.	Excerpt from the *ABSTRACT*: 'The article analyzes how Industry 4.0 triggers changes in the business models of manufacturing SMEs (small and medium-sized enterprises), by conducting a qualitative research with a sample of 68 German SMEs from three industries (automotive suppliers, mechanical and plant engineering, as well as electrical engineering and ICT).'

Step 3: Analysis of the papers

In this step, focus has been on the extraction by means of content analysis of the technological enablers, the barriers, the goals and their relationships within the texts of the 167 articles in the final sample, along with their relevant references. Two authors have read the body of the papers and extracted from each article the identified Industry's 4.0 enabling technologies, barriers, and goals as well as their relationships. For example, if an article mentioned Internet of Things as one Industry's 4.0 enabler, that technology was extracted. The authors read the articles multiple times and reconciled differences in the interpretation of the texts through face-to-face discussion.

Two sets of questions have been used to guide this extraction procedure. In this way, the authors had a template to identify the same kind of information in each paper. The first set has been used to identify the Industry's 4.0 enabling technologies, barriers, and goals:

- *What* are the enabling technologies of Industry 4.0?
- *What* barriers external to the factory hinder the adoption of the Industry's 4.0 technological enablers?

- *What* barriers internal to the factory hinder the adoption of the Industry's 4.0 technological enablers?
- *What* goals can be reached through Industry 4.0?

The second set of questions has been aimed to identify the relationships among the framework's building blocks:

- *Which* goals can be achieved through each of the Industry's 4.0 enabling technologies?
- *Which* barriers prevent the achievement of each goal?

Each author read the 167 articles aiming to find answers to the above questions. In the final round, information was gathered and synthetized. The file 'Supplementary material.xls' contains, among other things, the list of the enabling technologies, barriers and goals extracted from each of the 167 selected papers. The relationships among enabling technologies, goals and barriers are instead reported in Table 2 below.

Results

Descriptive findings

In this subsection, a brief overview of the time and journal distribution of the retrieved articles is provided (Thomé, Scavarda, and Scavarda 2016). Figure 2 reports the articles' time distribution.

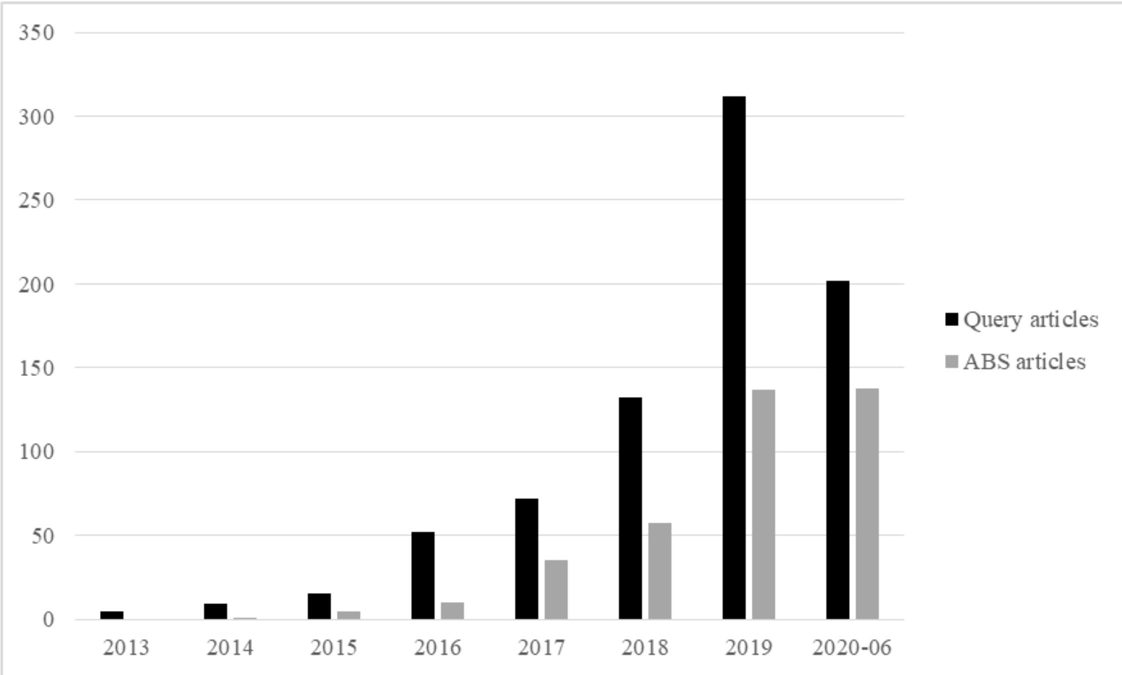


Figure 2 – Number of yearly publications in Industry 4.0

The plot shows the number of articles published yearly for the query in Table 1 including all the journals (in black) and those from the ABS list (in grey). The growth is exponential for both (considering that year 2020 is halved). As seen in the graph, the number of publications in ABS journals compared to the total number of publications is rising at a higher rate (in June 2020, it has already reached the number it had at the end of 2019). Industry 4.0 started out as a technical topic somewhat neglected in managerial literature; yet, this is evidently changing (Osterrieder, Budde, and Friedli 2020).

With regard to journals publishing Industry 4.0 papers, there are 240 total sources in the Scopus query. Out of these, 93 are ABS journals. The following figure (Figure 3) plots the frequencies of the ABS sources with more than 10 publications each summed up over the years.

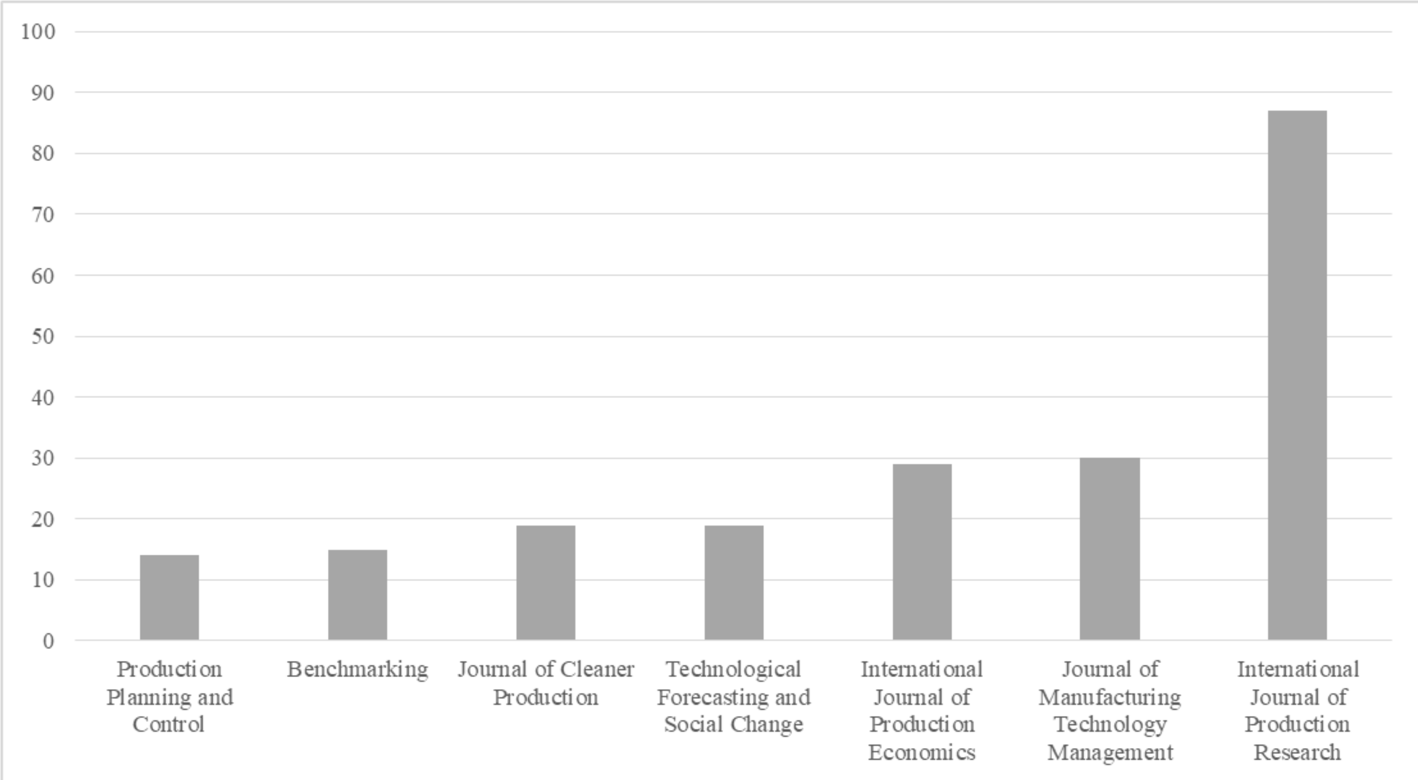


Figure 3 – Journals with the highest number of Industry's 4.0 articles

A number of things are significant to note. First, all the sources are homogeneous, having a number of articles between 15 and 30. The only exception, the *International Journal of Production Research*, is due to the high number of technical papers that are similar to the exclusion case in Table 1. Apart from this, the high concentration of managerial research in these journals is remarkable. Out of 93 ABS sources, only seven have more than ten articles. These seven sources have collectively 213 out of 383 articles. The Gini coefficient of the distribution is 0.65 (0 would mean a perfectly even distribution among the sources; 1 would mean a perfectly uneven distribution). To understand the magnitude of this concentration index, one should consider that the Gini coefficient of the income distribution of the United States, the seventh most unequal country in the world in income distribution, was 0.39 in 2017; while the index for the most unequal country, South Africa, was 0.62 in 2015 (OECD 2020). This means that Industry's 4.0 managerial research is highly concentrated in these journals, which are therefore good outlets to deepen it.

The framework's building blocks

The following four subsections examine the first four questions of this review: what the enabling technologies, internal and external barriers, and goals of Industry 4.0 are. These elements are the building blocks of the framework. They have been derived by analysing 167 papers in the sample as explained in the methodology. Some elements have been further subdivided (*a*, *b*, *c* and so on) to allow for a more thorough classification.

Enabling technologies

According to Liao et al. (2017) and Kang et al. (2016), the enabling factors of Industry 4.0 are its technologies. The technologies have been classified into nine mutually exclusive classes according to their context of application as explained below (Zangiacomi et al. 2020; de Sousa Jabbour et al. 2018; Moeuf et al. 2018).

Production Line Technologies. This class includes the technologies that can be found on the production line from the warehouse to the dispatching site. Examples of specific technologies belonging to this class are: 3D printing (Lu and Weng 2018), additive manufacturing (Rosin et al. 2020; Murmura and Bravi 2017; Niaki and Nonino 2017), collaborative and autonomous robots (Moeuf et al 2018; Müller et al 2018), and self-driving vehicles (Závadská and Závadský 2018).

Smart Worker Technologies (a, b). This class encompasses technologies empowering workers skills in production (*a*) and maintenance activities or more complex service operations (*b*) (Golan, Cohen, and Singer 2020; Patrucco, Ciccullo, and Pero 2020; Wang et al. 2020). Examples are devices such as smart glasses and smart gloves (Závadská and Závadský 2018), or technologies for augmented reality such as holograms (Kang et al 2016).

Smart Equipment Technologies. This class of technologies comprises devices that empower the monitoring, communicating, and interacting capabilities of physical objects such as sensors installed on physical devices (Kang et al 2016). Collectively, these technologies are known as Cyber Physical Systems (CPS) because they connect physical and cyber objects through the cyberspace (Crnjac et al 2017; Nayak et al 2016).

Computing Technologies. This class groups all the technologies empowering high-performing computing capabilities which enable massive simulation and optimization of the firms' activities (Brad et al 2018; Theorin et al 2017). An example is the virtualization of the factory environment along with the simulation and prototyping of its functioning (Angrish et al 2017; Jung et al 2017; Putman et al 2017).

Sharing Technologies (a, b). The technologies belonging to this class enable the sharing of resources such as machines and computing power, i.e., cloud manufacturing (Moghaddam and Nof 2018) and cloud computing (Moeuf et al 2018). These technologies make it unnecessary to own state-of-the-art equipment, which instead can be apportioned to multiple partners and used by each on demand (*a*) (Nodehi et al. 2017). Manufacturers willing to share their resources with others can employ this paradigm and make an active use of these shared technologies to create new business models (*b*) (Calabrese, Levialdi Ghiron, and Tiburzi 2020).

Smart Product Technologies (a, b). The technologies in this class are the counterparts, installed on products, of *Smart Equipment Technologies* (Porter and Heppelmann 2015). In fact, *Smart Product Technologies* involve equipping final products, rather than the factory's physical assets, with technological elements that enable their remote monitoring and allow them to be autonomous (*a*) (Bokrantz et al. 2017). Similarly, some of these technologies can be used as a platform for the producers active involvement in the customer's activities (*b*) (Frank, Dalenogare, and Ayala 2019).

Data Analytics Technologies. This class comprises all of the technologies that allow the management of complex data sets (big data) coming from outside the factory (Shou, Zhao, and Chen 2019; Zhong et al. 2017) mostly used in the development of new services for customers (Arnold et al. 2016).

Network Technologies. This class groups technologies enabling the communication among objects by means of a network infrastructure (Hwang et al. 2017). A prominent technology found in this class is the Internet of Things (IoT), which is taken by some scholars to be the single most fundamental technology enabling the utilization of the Industry's 4.0 paradigm (Islam et al. 2020; Kiel, Arnold, and Voigt 2017). Indeed, network infrastructure is the feature that allows communication between sensors installed on physical equipment and products (e.g. RFID), as well as autonomous things-to-things collaboration (Lee and Lee 2015).

Cyber-Security Technologies. This last class collects technologies that consist of advanced systems of data protection. Basically, these technologies secure communication channels and storage sites and certify information validity. Overall, they guarantee a successful implementation of the Industry's 4.0 paradigm (Moeuf et al. 2018). For instance blockchain technologies, a specific cyber-security technology, have been used to certify the origin of physical goods from supply chains spread across multiple countries (Dolgui et al. 2020; Garzoni et al. 2020; Kouhizadeh, Zhu, and Sarkis 2019).

External barriers

Industry's 4.0 journey can be thwarted by the presence of barriers or challenges which are outside the managers own control; they depend on contingent factors such as the non-existence of adequate technological devices or underdeveloped regulatory frameworks (Raj et al. 2020; Reischauer 2018). The aim of this section is to analyse the five external barriers that have emerged.

Communication Standards. The first external barrier is the lack of communication standards for machines sold by different vendors (Müller et al. 2018; Janak and Hadas 2015; Leitao et al. 2015). This lack of standard communication protocols is particularly relevant for Industry 4.0 because of the growing number of autonomous machines taking part in the value creation process (Moeuf et al. 2018; Wang et al. 2016). Due to the strong negative impact of this barrier on the adoption of Industry 4.0, Liao et al. (2017) have identified this as a top priority.

Regulatory Framework. This barrier focuses on the requisite to improve the regulatory framework to protect corporations, employers, and customers against the malicious use of information gathered by exploiting the pitfalls of Industry's 4.0 data exchange mechanisms (Kusiak 2018; Kim and Chang 2014; Merfeld 2014). Indeed, the increase in the volume of data exchanged has accelerated privacy apprehension on the users side; whereas from the firms perspective, it has increased the concerns about the protection of proprietary technologies and patents (Crnjac et al. 2017; Kagermann et al. 2013). Compatibility among the different countries' legal systems is especially relevant and must be taken into account given the distribution pattern of the stakeholders participating in today's market transactions (Kusiak 2018; Strange and Zucchella 2017).

Infrastructure. This external barrier reveals the necessity for governments to provide network infrastructures suitable for the high-volume, high-quality data exchange typical of Industry's 4.0 technologies (Kang et al. 2016). In fact, existing regional differences in bandwidth speed, since they create unequal conditions for competition and hinder the full exploitation of the Industry's 4.0 potential, discourage managers from beginning such transformative journey (Kiel, Arnold, and Voigt 2017).

Competence Shortage. This external barrier targets the shortage of technical skills in the labour force (employed or potentially employable) caused by the rapid evolution of the needed skills (Sung 2017; Li 2017). Governments are addressing this deficiency, detrimental to the adoption of the Industry's 4.0 paradigm (Arnold et al. 2016), by creating learning centres to teach new technical skills (Kagermann et al. 2013).

Government Incentives. This last external barrier limits the financial resources for the initial high cost of switching to Industry's 4.0 technologies, particularly for small or medium factories. Until recently, national government incentives such as tax exemptions have not solved the problem nor have specific technological programs been implemented (Lin et al. 2018; Müller et al. 2018).

Internal barriers

Industry's 4.0 journey is also hindered by a number of internal barriers from strategy and analysis to optimization and planning upon which managers should directly act to achieve their transformation goals (Raj et al. 2020; Zangiacomi et al. 2020; Schneider 2018). The barriers extracted from the literature are reported below.

Employees Reorganization. This barrier deals with the reallocation of the workforce because of the digital transformation (Krzywdzinski 2017; Schlüter and Sommerhoff 2017). In fact, new technologies bring structural changes in workforce type, reflected in the employees' roles, as well as in job redundancies (Crnjac et al. 2017).

Firm Reorganization. This barrier shows the changes caused by Industry's 4.0 technologies at the organizational level (Fatorachian and Kazemi 2018; Strange and Zucchella 2017). Indeed, by adopting technologies such as cloud manufacturing, a factory's network of partnerships, as well as its physical location, are likely to change (Murmura and Bravi 2017). Even the structure of firms can switch, for example with the addition of business units for the monetization of data (Müller et al. 2018).

Investments. The heavy renovation of the firms' resources (machines and people) requires a high initial expenditure, which firms might not be prepared to confront (see also the external barrier *Government Incentives*). Thus, the high costs to carry out an Industry's 4.0 transformation are often cited as an impeding barrier (Müller et al. 2018; Tortorella and Fettermann 2017).

Complex Systems Installation. Highly technological equipment requires complex installation and deployment (Theorin et al. 2017). Therefore, Industry's 4.0 transformative journey can be inhibited by machine and sensor installation problems (Liao et al. 2017).

Complex Systems Design and Management. This barrier considers the difficulties in designing and managing the architecture of complex systems composed of automatic machines and sensors (Kim 2018; Jung et al. 2017). For example, it focuses on the problems faced by engineers in designing manufacturing systems which are reliable and resilient, i.e., capable of maintaining the flow of the production process despite the failure of a single component (Wang et al. 2018; Sung 2017). Another problem linked to this barrier is optimizing and coordinating (i.e. managing) the operations of Industry's 4.0 autonomous systems, all requiring advanced scheduling techniques to be successful (Brad et al. 2018; Lv and Lin 2017).

Information Management. This barrier reflects the difficulties inherent in managing and organizing a large quantity of information (i.e. with high volume, accuracy, variety) generated by technologies such as cyber-physical systems and RFID-sensors (Jabbour et al. 2018; Wang et al. 2018). It is often caused by the firms' outdated network infrastructure, which was not designed to support the processing of gigabytes of data coming in seconds. This barrier is linked to the lack of professionals specialized in this kind of activities (Angrish et al. 2017; Merfeld 2014).

Information Profitable Usage (a, b). Conceptually different from the preceding one that focuses on the planning and organization of information, this barrier deals with the difficulties experienced by manufacturers in making profitable use of the enormous amount of available information. From an internal perspective, it refers to the conversion of information into strategic and tactical intelligence (*a*) (Polyvyanyy et al. 2017); from an external perspective, it refers to the development of business activities converting information into extra cash flows (*b*) (Müller et al. 2018).

Safety and Security (a, b). This barrier accounts for the firms' lack of internal capabilities to guarantee the security of data exchange and storage in such a hyper-connected manufacturing environment (*a*) (Preuveneers et al. 2017; Strozzi et al. 2017). In addition, this barrier includes the safety of the personnel operating at close contact with autonomous machines (*b*) (Liao et al. 2017). This barrier is conceptually separated from the *Regulatory Framework's* external barrier, which focuses on the structural lack of adequate laws regulating the firms' activities in a digital environment.

Product Customization. Despite the willingness to serve individual customers, technical difficulties arise in projecting micro-scale plants capable of developing products with a great variety of features (Müller et al. 2018; Murmura and Bravi 2017). This barrier must be distinguished from that of capitalizing on information (i.e. *Information Profitable Usage*), explained in the previous paragraphs, and from that of redesigning factories' value creation models (i.e. *Value Creation Redesign*) explained below.

Customer Preparedness. Although new technologies allow for the provision of new features on products, managers should ensure that they provide the suitable offering to the right customer. As observed by some empirical studies, not all customers are ready, or even worse, willing, to pay a premium price for additional features (Müller et al. 2018; Kiel et al. 2017).

Competence Shortage. This internal barrier measures the absence of skills in the workforce and is the same as the external *Competence Shortage* barrier of the previous section. In this case, the lack of competence is attributed to factors internal to the firms (e.g. lack of training, or ageing workforce), rather than to an intrinsic shortage of suitable labour. All the studies dealing with this problem agree that it can be overcome by providing training programmes specific to the requirements of the various Industry's 4.0 technologies (Gorecky et al. 2017).

Cultural Resistance (a, b, c). This barrier indicates Industry's 4.0 problems created by the employees' cultural backgrounds (de Sousa Jabbour et al. 2018). From a managerial perspective, specific cultural barriers are the scepticism about the potential benefits and problems of new technologies (Murmura and Bravi 2017; Hirsch-Kreinsen 2016), and the absence of a customer-oriented culture (*a*) (Kiel et al. 2017). Average and low-qualified workers instead are reluctant to change *(b)* (Sung 2017) and fear being controlled *(c)* (Fatorachian and Kazemi 2018).

Technology Infancy. Not all technologies might be at an acceptable level of development in every industry at the same time; thus, managers in specific industries might regard them as unsuitable for their needs (Porter and Heppelmann 2014; Porter 2008). This has been true for some managers in the Italian wood industry who consider additive manufacturing technologies to be too embryonic for systematic installation on their production lines (Murmura and Bravi 2017).

Technology Obsolescence. This barrier is the complement of the precedent one: managers of a specific sector might regard technologies as too rapidly developing for the investment to be worthwhile (Qu et al. 2017).

Partnership Redesign. Industry's 4.0 transformative journey brings with it the possibility of sharing physical resources (*Sharing Technologies*), which implies that coordination and cooperation of businesses are fundamental (Schneider 2018). This necessity to redefine partners is due to their nonhomogeneous technological development (Agarwal and Brem 2015).

Value Proposition Redesign. The last internal barrier is the inability of managers to think of new value propositions to reap the benefits of Industry 4.0 (Schneider 2018). Although there is diffuse awareness of the business model changes caused by the introduction of new technologies (Arnold et al. 2016), manufacturers are still looking for new ways of turning them into radical paradigm changes (Müller et al. 2018). This barrier has to be distinguished from others such as *Product Customization*. The latter refers to a change in the usual way of doing business (i.e. manufacture of products) in order to meet a customer requirement, whereas the former represents a radical shift in the way manufacturers do business (e.g. addition of services to products or provision of capabilities rather than products).

Goals

This section reports the goals that can be achieved at the end of a successful Industry's 4.0 transformative journey.

Productivity. Industry 4.0 has a potentially positive impact on a series of activities, such as employee's optimization (Kim 2018; Ortíz et al. 2018), unit cost reduction (Kumar et al. 2018; Brad et al. 2018), unit time reduction (Moeuf et al. 2018; Jung et al. 2017), and inventory and warehouse management (Buer et al. 2018; Qu et al. 2017).

Quality. The monitoring capabilities enabled by the new technologies have the potential to bring a sensible reduction in the number of errors in operations such as order picking and dispatching (Lee et al. 2018), as well as in those relevant to production (Buer et al. 2018; Strozzi et al. 2017). Therefore, Industry 4.0 improves the quality of factories' operations (Yadav, Shankar, and Singh 2020).

Profitability. Linked to the two preceding goals, Industry's 4.0 adoption leads to an increase in financial profitability (Kiel, Arnold, and Voigt 2017), which is indeed indicated by manufacturers as a major accomplishment (Fatorachian and Kazemi 2018; Geissbauer, Vedso, and Schrauf 2016).

Resource efficiency. This goal refers to the impact that Industry 4.0 can have on sustainability. Such an impact is mostly referred to as environmental sustainability achievements, i.e. a reduction in resource consumption (energy and material) during the production phase (Bai et al. 2020; Li, Dai, and Cui 2020; Tiwari and Khan 2020). This achievement is also linked to *Productivity*.

Material circularity. This goal accounts for the capability of manufacturers to enhance the value of material resources throughout their lifecycle. This goes from better waste management to improved product refurbishment routines (Tiwari and Khan 2020; Jabbour et al. 2019; Kerin and Pham 2019).

Agility. Another relevant goal of Industry 4.0 is its positive impact on supply chain agility, i.e., its ability to cope with a difficult to predict demand on a wide variety of product variants (Dolgui et al. 2020; Haleem and Javaid 2019). In addition, Industry 4.0 allows the rapid redesign of the value streams (Tortorella et al. 2020).

Customer Sensing (a, b). This goal displays the improved ability to capture (i.e. to sense) the requirements of each single customer through activities such as usage monitoring, virtual product development (*a*), and data analytics (*b*) (Bordeleau, Mosconi, and de Santa-Eulalia 2020; Müller et al. 2018; Ogu et al. 2018). Such increased customer proximity, categorized as a goal *per se*, has to be distinguished from the ability to respond effectively to customer requirements by means of product or content customization, which is dealt with in the following two items (*Product Customization* and *Content Customization*).

Product Customization. This goal refers to the ability of manufacturers to provide products tailored to the requirements of each customer, i.e., the ability to accommodate product changes with minimum costs of production line reconfiguration, even for low-volume batches (Culot et al. 2020; de Sousa Jabbour et al. 2018; Müller et al. 2018). This goal is complementary to the preceding one. Through *Customer Sensing,* manufacturers can see what customers are looking for; whereas with *Product Customization,* manufacturers produce a new product to fit the customer's requirements.

Content Customization. This particular goal refers to the capability of manufacturers to provide personalized content (e.g. a software feature or usage statistics) to individual customers (Calabrese, Levialdi Ghiron, and Tiburzi 2020; Wang et al. 2018; Arnold et al. 2016). In contrast with the preceding goal, this fulfils those customer needs related to content-based features, rather than product-based ones.

Monitoring. Some Industry's 4.0 technologies (see *Smart Equipment* and *Smart Product Technologies*) allow constant monitoring of machines and products, empowering remote diagnostics, preventive and proactive maintenance (de Sousa Jabbour et al. 2018; Závadská and Závadský 2018), control of product functions and of user experience (Moeuf et al. 2018), and internal audit on workers' and machines' performance (Bokrantz et al. 2020a; Bokrantz et al. 2020b; Lu and Weng 2018).

Safety and Security (a, b, c). This goal reflects increased employee safety and security thanks to the assignment of drones and robots to risky tasks (*a*) (Schneider 2018; Strange and Zucchella 2017). Furthermore, it includes the improvement of the safety and security of customers (*b*) (Queiroz et al. 2020) and transactions (*c*) (Dolgui et al. 2020) through smart product and cybersecurity technologies.

Information Sharing (a, b). This goal refers to the improvements in data collection and exchange capabilities internal to the firm, i.e. within and among departments (*a*) (Gorecky et al. 2017; Liao et al. 2017); and external to the firm, i.e. in coordination among business partners (*b*) (Zheng and Wu 2017; Lee and Lee 2015). This goal acts as a complement to *Decision-Making* and *Material Circularity*.

Decision-Making. This goal comes from the exploitation of the collected information for proactive decision-making activities such as optimised production and supply chain operations (Fatorachian and Kazemi 2020; Kumar et al. 2018), inventory management (Strange and Zucchella 2017), and demand management (Zou et al. 2017).

Competitiveness in Own Sector. This goal refers to the potential increase of competitiveness deriving from the adoption of the Industry's 4.0 paradigm, which is often reported as one of its main goals (Li, Dai, and Cui 2020; Weking et al. 2020; Müller et al. 2018).

Competitiveness Outside Sector. This goal refers to the ability of manufacturers to move profitably into new business sectors, to reach out to new customers, and to exploit unexplored revenue models (see also the *Value Proposition Redesign* internal barrier) (Bordeleau, Mosconi, and de Santa-Eulalia 2020; Weking et al. 2020). For example, by increasing customer proximity and extending 'what manufacturers can do' in terms of capabilities, new technologies have the potential to transform them into product-service providers (Kohtamäki et al. 2013; Ulaga and Reinartz 2011), thus enabling them to compete with service businesses as well (Story et al. 2017; Strange and Zucchella 2017; Sung 2017). Industry 4.0 also represents, as reported by Müller, Buliga, and Voigt (2018) and Murmura and Bravi (2017), a chance for manufacturers to redefine their value-capturing models, for example by opening up new revenue streams and payment schemes.

The Industry 4.0 Framework

This section reports the relationships between Industry's 4.0 enabling technologies, barriers and goals. They have been obtained, as in the previous case, by analysing the 167 papers in the sample. First, the relationships have been arranged into a table (Table 2). Then, based on the relationships in the table, a framework has been built (Figure 4). The technologies have been categorized into evolutionary and revolutionary enablers, according to the type of transformation they produce compared to the traditional product business model (Baden-Fuller and Morgan 2010). This is a common approach in business literature dealing with innovation (Schniederjans 2018; Johnston et al. 2001; Dewar and Dutton 1986), which has nonetheless been adopted only by Calabrese, Levialdi Ghiron, and Tiburzi (2020) for Industry 4.0. Such a classification helps differentiate between Industry's 4.0 incremental and radical changes (Bibby and Dehe 2018; Xu, Xu, and Li 2018). Also regarding the barriers and the goals, multiple entries (a, b, c, and so on) have been included in order to differentiate among the various subcategories.

Table 2 – Relationships among Industry's 4.0 enablers, barriers, and goals

Evolutionary enablers	**Barriers (top external; bottom internal)**	**Goals**	**References**
Production line technologies	Communication standards; Government incentives. Employee reorganization; Firm reorganization; Investments; Product customization; Complex systems installation; Complex systems design and management.	Productivity; Quality; Profitability; Resource efficiency; Product customization; Agility; Safety and security (a); Competitiveness in own sector.	Culot et al. 2020; Rosin et al. 2020; Gershwin 2018; Kim 2018; Kusiak 2018; Lin et al. 2018; Moeuf et al. 2018; Závadská and Závadský 2018; Calitz et al. 2017; Li 2017; Murmura and Bravi 2017; Strange and Zucchella 2017.
Smart worker technologies (a)	NA Cultural resistance (b, c);	Productivity; Quality; Safety and security (a); Information sharing (a); Decision-making.	Golan, Cohen, and Singer 2020; Patrucco, Ciccullo, and Pero 2020; Wang et al. 2020; Alejandro Germán Frank, Dalenogare, and Ayala 2019; Fatorachian and Kazemi 2018;

			Wang et al. 2018; Strange and Zucchella 2017; Sung 2017
Smart equipment technologies	NA Investments; Complex systems design and management; Information management; Safety and security (b); Information profitable usage (a).	Quality; Agility; Monitoring; Information sharing (a).	Buer et al. 2018; de Sousa Jabbour et al. 2018; Gershwin 2018; Moeuf et al. 2018; Müller, Buliga, and Voigt 2018.
Computing technologies	NA Complex systems design and management; Information profitable usage (a).	Productivity; Decision-making.	Brad et al. 2018; Ortíz et al. 2018; Putman et al. 2017; Theorin et al. 2017.
Sharing technologies (a)	NA Firm reorganization; Employee reorganization; Complex systems design and management; Partnership redesign.	Productivity; Profitability; Agility; Product customization.	Calabrese, Levialdi Ghiron, and Tiburzi 2020; Bonfanti et al. 2018; Moghaddam and Nof 2018; Nodehi et al. 2017.
Smart product technologies (a)	NA Technology obsolescence.	Customer sensing (a); Safety and Security (b); Competitiveness in own sector.	Alejandro Germán Frank, Dalenogare, and Ayala 2019; Wang et al. 2018; Bokrantz et al. 2017; Arnold et al. 2016; Porter and Heppelmann 2014.
Network technologies	Communication standards; Infrastructure. Complex systems installation; Complex systems design and management; Information management; Safety and security (a).	Productivity; Information sharing (a); Monitoring; Competitiveness in own sector.	Fatorachian and Kazemi 2018; Moeuf et al. 2018; Liao et al. 2017; Preuveneers et al. 2017; Laudien and Daxböck 2016.
Cyber security technologies	Regulatory framework. Technology infancy.	Agility; Information sharing (a, b); Safety and security (c).	Dolgui et al. 2020; Garzoni et al. 2020; Tortorella et al. 2020; Kouhizadeh, Zhu, and Sarkis 2019; Kusiak 2018; Moeuf et al. 2018.

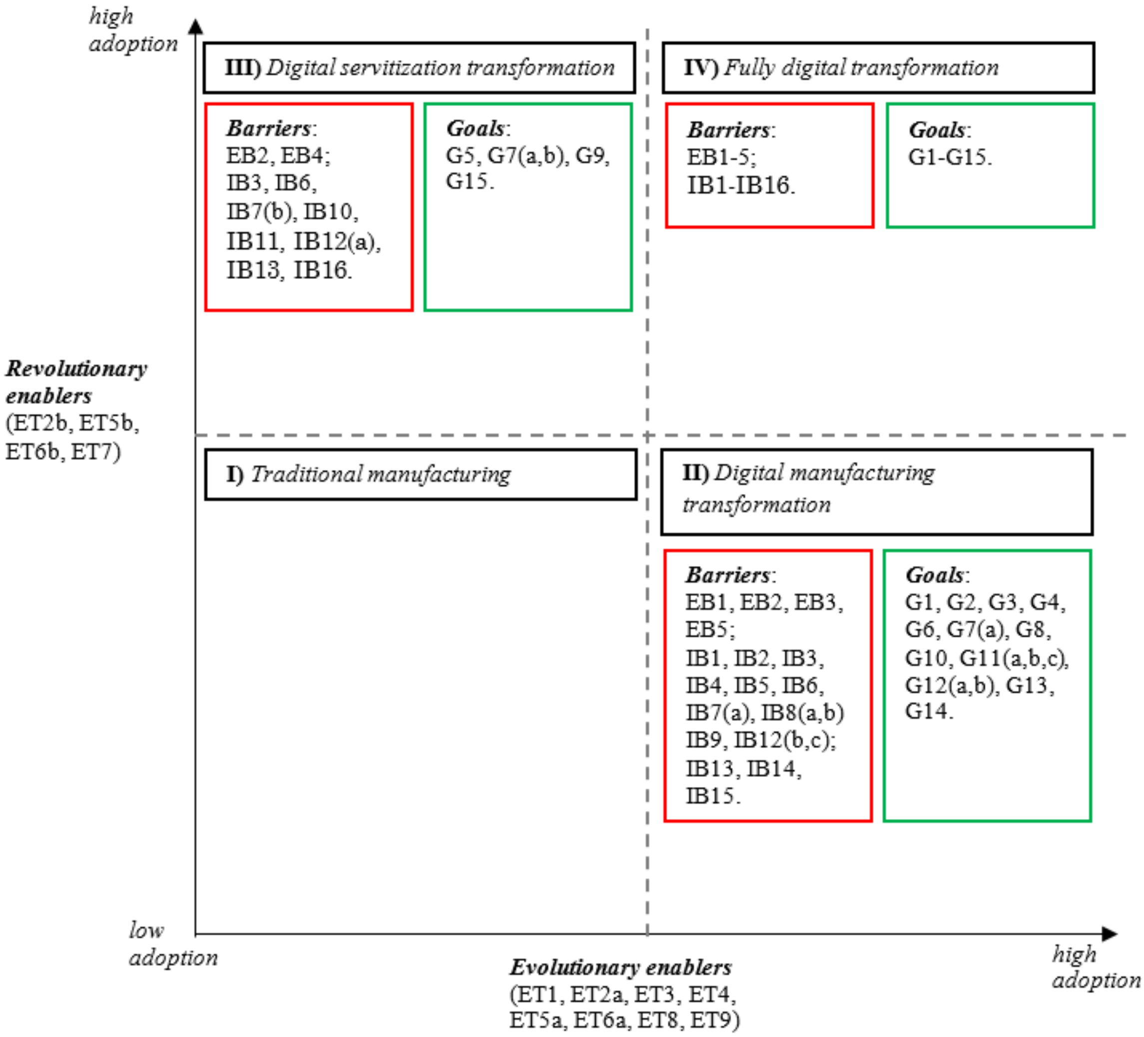
Revolutionary enablers	**Barriers (top external; bottom internal)**	**Goals**	**References**
Smart worker technologies (b)	NA Cultural resistance (a). Technology infancy; Customer preparedness.	Customer sensing (a); Monitoring; Material circularity; Competitiveness outside sector.	Alejandro Germán Frank, Dalenogare, and Ayala 2019; Ayala et al. 2017; Elia, Gnoni, and Lanzilotto 2016.
Sharing technologies (b)	NA Investments; Cultural resistance (a); Value proposition redesign.	Competitiveness outside sector.	Calabrese, Levialdi Ghiron, and Tiburzi 2020; Garcia Martin, Schroeder, and Ziaee Bigdeli 2019; Schroeder et al. 2019.
Smart product technologies (b)	NA Information management; Information profitable usage (b); Customer preparedness; Value proposition redesign.	Customer sensing (a, b); Content customization; Monitoring; Competitiveness outside sector.	Alejandro Germán Frank, Dalenogare, and Ayala 2019; Müller, Buliga, and Voigt 2018; Porter and Heppelmann 2014.
Data analytics technologies	Competence shortage; Regulatory framework. Investments;	Customer sensing (b); Content customization; Competitiveness outside sector.	Bordeleau, Mosconi, and de Santa-Eulalia 2020; Weking et al. 2020; Shou, Zhao, and Chen 2019; Kumar et al. 2018;

	Information management; Information profitable usage (b); Cultural resistance (a); Competence shortage; Value proposition redesign.	Jabbour et al. 2018; Müller, Buliga, and Voigt 2018; Wang et al. 2018; Polyvyanyy et al. 2017; Strange and Zucchella 2017; Sung 2017; Tortorella and Fettermann 2017; Arnold et al. 2016.

Taking the first line of Table 2 as an example, productivity can be obtained if production line technologies are adopted, provided that some internal and external barriers (e.g. employee reorganization) are considered. It is clear, through this brief example, how the relationships in the table can serve as a guide for managers to reach certain Industry's 4.0 goals (Culot et al. 2020).

To further connect Industry's 4.0 enabling technologies, barriers and goals, the framework in Figure 4 has been developed. This framework has the evolutionary enablers on the x-axis and the revolutionary ones on the y-axis. According to the amount of each enabler adopted, the manufacturers will be in one of the four quadrants, which have been labelled referring to the type of digital transformation occurring (no transformation, digital manufacturing transformation, digital servitization transformation, fully digital transformation) (Kohtamäki et al. 2020; Uhl and Gollenia 2016). The goals and barriers have been apportioned to each enabling technology according to the relationships in Table 2.

Manufacturers in the first quadrant undergo no transformation. Manufacturers in the second quadrant retain their traditional way of doing business and increase the efficiency of their operations (G1-4, G14) (Culot et al. 2020; Rosin et al. 2020; Baden-Fuller and Morgan 2010). They also improve the flexibility of their production process, i.e., their capability to customize small production batches (G6, G8) (Fatorachian and Kazemi 2020; Bonfanti, Del Giudice, and Papa 2018). By digitalising their production operations, manufacturers in this quadrant increase employees' safety and security (G11) and managers' decision-making capabilities (G12-13) (Fatorachian and Kazemi 2018; Moeuf et al. 2018). Manufacturers in the third quadrant forgo their traditional business of selling products and engage in value co-creation activities with their customers (G15), for example by performing value-added activities on product-generated data (Abou-foul, Ruiz-Alba, and Soares 2020; Sjödin, Parida, Kohtamäki, et al. 2020). In this quadrant, manufacturers change the type of relationship they have with their customers. They go from a transactional relationship, based on the one-off selling of products, to a relational one, based on the provision of customized product-service solutions (G5, G7, G9) (Kharlamov and Parry 2020; Baden-Fuller and Morgan 2010). In the last quadrant, manufacturers use Industry's 4.0 technologies to enhance their traditional operations as well as to bring about radical changes in their offering (Sjödin, Parida, Jovanovic, et al. 2020). In this quadrant, manufacturers seek to exploit the digital synergy, i.e., to take advantage of the interaction between digitization in the production process and in the service offering (Kharlamov and Parry 2020; Sklyar et al. 2019).



Legend

ET1 (Production line technologies); ET2 (Smart worker technologies); ET3 (Smart equipment technologies); ET4 (Computing technologies); ET5 (Sharing technologies); ET6 (Smart product technologies); ET7 (Data analytics technologies); ET8 (Network technologies); ET9 (Cyber security technologies).

EB1 (Communication standards); EB2 (Regulatory framework); EB3 (Infrastructure); EB4 (Competence shortage); EB5 (Government incentives).

IB1 (Employee reorganization), IB2 (Firm reorganization), IB3 (Investments), IB4 (Complex systems installation), IB5 (Complex systems design and management), IB6 (Information management), IB7 (Information profitable usage), IB8 (Safety and security), IB9 (Product customization), IB10 (Customer preparedness), IB11 (Competence shortage), IB12 (Cultural resistance), IB13 (Technology infancy), IB14 (Technology obsolescence), IB15 (Partnerships redesign), IB16 (Value proposition redesign).

G1 (Productivity), G2 (Quality), G3 (Profitability), G4 (Resource efficiency), G5 (Material circularity), G6 (Agility), G7 (Customer sensing), G8 (Product customization), G9 (Content customization), G10 (Monitoring), G11 (Safety and security), G12 (Information sharing), G13 (Decision-making), G14 (Competitiveness in own sector), G15 (Competitiveness outside sector).

Figure 4 – The Industry 4.0 framework

As seen in the framework, some goals and barriers are shared among the four quadrants, i.e., they are relevant to Industry 4.0 (e.g. IB3 – investments). On the other hand, others are applicable to certain transformations. For example, the G1 goal (productivity) is achieved only if evolutionary enablers such as production line technologies are adopted. Together with the description of its four quadrants, the framework can be used to discuss the transformative journeys of firms from one point to the other. There are in total 16 such journeys (4^2). These include journeys starting from one quadrant and ending in another one (e.g., starting in quadrant II and ending in quadrant III); reverse journeys (e.g., journeys from quadrant III to quadrant II); and journeys in the same quadrant (e.g., starting in quadrant II and ending in quadrant II). All that is needed to analyse a journey is the barriers and goals in each quadrant as provided above. Two firms' transformative journeys are presented in the next section to illustrate the use of the framework.

Industry's 4.0 Transformative Journey: the Web Application

The framework in Figure 4 summarizes the relationships in Table 2. It provides a description of the four states that can be reached at the end of each journey. To give managers information about how their own journey will materialize, a web application based on the framework's content has been built. It can be found at this link (the app runs on a remote server. So, depending on how crowded it is, it might take up to a couple of minutes to launch). The app is written in Python, a general-purpose programming language that can be used for many sorts of tasks including web programming, big data analytics, and scientific computing. The remote server used to run the app is called Binder, a web service that allows the creation of custom computing environments in the cloud (Jupyter et al. 2018). The repository where the code and the configuration files are stored can be found at this link.

Potential users of this web application are asked to assess on a Likert scale the extent to which they adopt the evolutionary and revolutionary technological enablers of Industry 4.0 and to indicate the goals they want to achieve. A plot similar to the one in Figure 4 is sketched based on the answers to these sets of questions. The plot summarizes the journey to reach the desired goals. The current position of the manufactures is indicated with a black point. The desired position, in terms of goals, is shown with a green point. The needed amount of evolutionary and revolutionary technological enablers to reach the desired goals can be read on the axes. The barriers that will be encountered during the journey are plotted in the background in two different shades of red. Enablers, barriers and goals are given the same names as those that can be found in this paper. Respondents, after visualizing their journey, can refer back to the paper to elaborate on the items most relevant to their particular simulation. This is an innovative approach for managers to interact with academic research in this field.

To see how this web application can be used, the managers at two multinational companies have been interviewed. One company is a multinational corporation headquartered in Switzerland operating mainly in robotics, power, heavy electrical equipment and the automation technology areas (Case A). The company has about 144k employees worldwide and a turnover of approximately $27bn (2019). The other company (Case B) is a multinational corporation headquartered in the US manufacturing medical devices, pharmaceutical products and consumer packaged goods. It has about 132k employees and a turnover of approximately $82bn dollars (2019). The interviews lasted about 1h30m and were carried out via web (Case A) and face to face (Case B). The interviewees are senior managers with more than 20 years of experience at their respective companies.

Figure 5 reports the results of the technological and goal assessments for companies A and B performed by the managers during the interviews. The answers to the technological and goal assessments are reported aside. The resulting plots are on a shared x-y axis to ease the comparison of the two cases. Only the most prominent barriers are labelled in the Figure. In the web app, hovering with the mouse on each barrier shows its label.

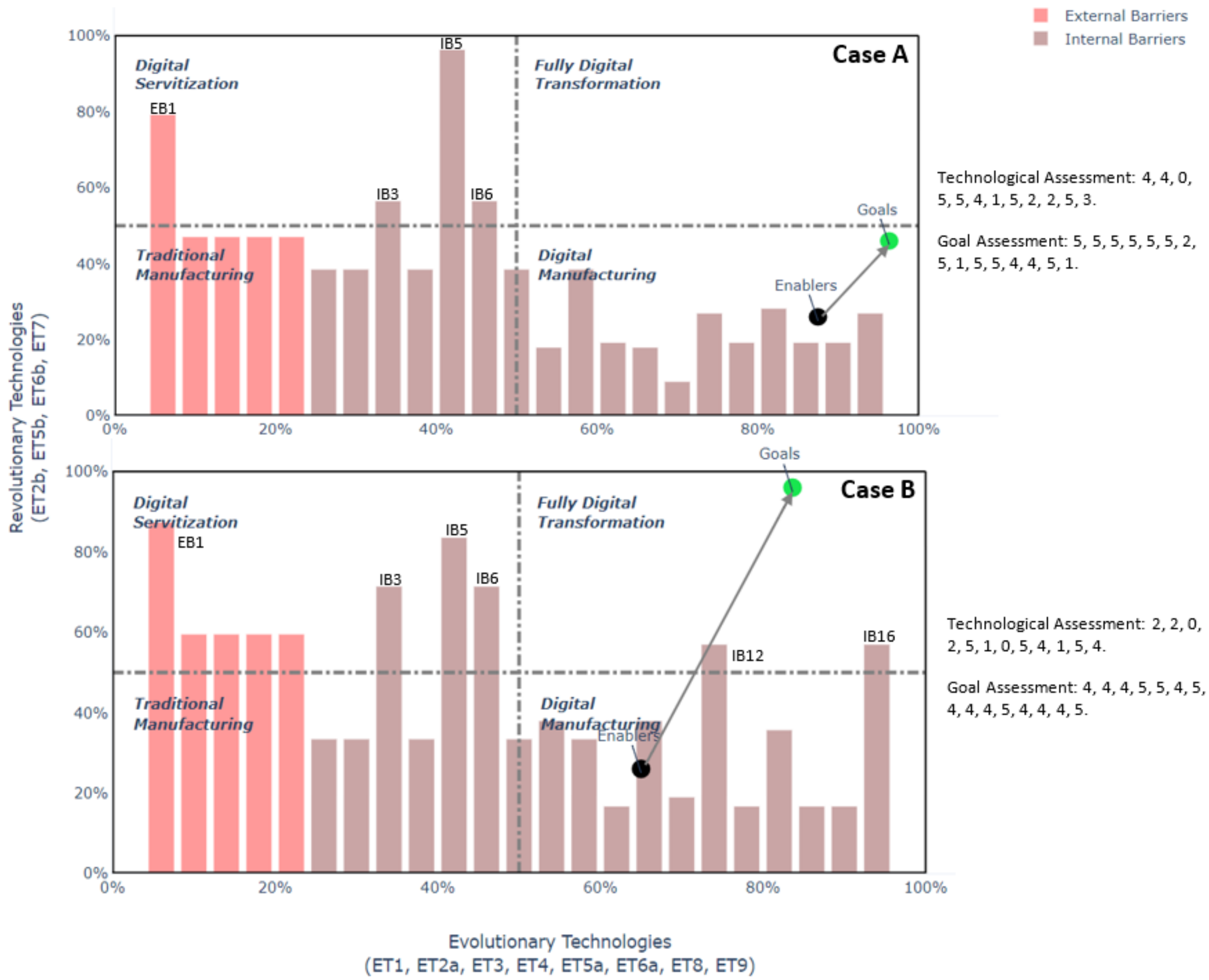


Figure 5 – Two Industry 4.0 journeys

The two journeys have similarities and differences mainly reflecting the companies' different views on Industry 4.0. Each company has a different trajectory because of its diverse view of Industry 4.0. In the first journey, company A aims at pushing its digital manufacturing capabilities to the next level, further improving its position as a market leader. In doing so, it is likely to encounter four of the most specific barriers of a digital manufacturing journey: communication standards (EB1), investments (IB3), complex systems design and management (IB5), and information management (IB6). By adopting technologies such as robots and sensors, it is likely that company A will face the challenge of managing the complexity of a fully digital environment (EB1, IB5-6) as well as the high costs required to purchase the required machines and sensors (IB3). Case B is similar, in this respect, to case A. At company B, the manager feels that in the future manufacturing will be more digital than it is today, so he wants to pursue that trajectory in advance. Similar to case A, his company will probably face the barriers EB1, IB3-5-6.

The companies differ in the role they assign to digital servitization. For company A, the offering of digital services will 'never be the core value proposition of a manufacturer'. Therefore, it will pursue it moderately. On the other hand, the manager at company B believes that in his case digital servitization is worth pursuing. During the interview, he pointed out that the company has already attempted this; but reinventing the value proposition (IB16) has proven to be 'a difficult challenge'. He is nonetheless willing to move in that direction. As shown in the output, the company will have to increase his amount of revolutionary technological enablers. In doing so, it will also have to pay attention to cultural resistance (IB12) from managers unwilling to change the nature of the company's value proposition (*a*), and from employees reluctant to change and fearing round the clock control (*b*, *c*).

The above paragraph shows how the software together with the paper can be used as a tool to analyse the Industry's 4.0 prospective journey. It shows the results that managers can obtain while steering their companies through this transformation.

Discussions

A number of scholars have called for the creation of frameworks and tools devised to support managers in transforming their organizations according to the Industry's 4.0 paradigm (Chiarini, Belvedere, and Grando 2020; Culot et al. 2020; Wagire et al. 2020; Weking et al. 2020; Bibby and Dehe 2018). As argued by Culot et al. (2020), the majority of the managerial literature so far has dealt with this topic by providing descriptions and classifications of the various Industry's 4.0 technological enablers. While this approach is useful in making managers aware of new innovation, it falls short in aligning the choice of the technological enablers to specific business goals. This paper, through a systematic literature review, develops a framework and a web application to guide managers in finding the right technological enablers for their goals (Chiarini, Belvedere, and Grando 2020; Weking et al. 2020).

Compared to previous technological assessments, which tend to see the adoption of the various enablers as linear and progressive (Culot et al. 2020; Frank, Dalenogare, and Ayala 2019; Bibby and Dehe 2018), this paper follows Calabrese, Levialdi Ghiron, and Tiburzi (2020), who have argued for a classification of the technologies according to the type of innovation they enable. Some technologies facilitate the evolution of the manufacturers' way of doing business. These technologies make product manufacturing more efficient and effective (Rosin et al. 2020). On the other hand, certain technologies lead to revolutionary changes in the manufacturers' business, such as the offering of digital products as services (Kohtamäki et al. 2020; Weking et al. 2020). Thus, the different utilization of Industry's 4.0 technological enablers leads to diverse destinations at the end of an Industry's 4.0 transformative journey.

Starting from traditional manufacturing, three transformations can be achieved at the end of the Industry 4.0 journey: digital manufacturing, digital servitization, and fully digital transformation. Referring to the quadrants in Figure 4, these are the transformative journeys from quadrant I) to quadrants II), III), and IV) respectively. These can be regarded as the three main Industry's 4.0 journeys, which will be taken by all traditional manufacturers willing to embrace this new paradigm. For this reason, they are discussed here. Clearly, if the starting point is different, as is the case of the companies analysed in the previous section, other transformative journeys will take place. As demonstrated in the previous section, the analysis of such journeys can be easily performed by using the web application along with the description of each quadrant's goals and barriers (Table 2 and Figure 4).

Digital manufacturing transformation (II) can be achieved by adopting technologies such as robots and drones, 3D printing, computing, and blockchain. The most relevant feature of this transformation is that manufacturers retain the traditional business paradigm (selling products) while at the same time improve their routines (Bibby and Dehe 2018; Lu 2017). Productivity and quality are the major goals of this type of transformation (Yadav, Shankar, and Singh 2020; Tortorella, Giglio, and van Dun 2019). The fact that digital manufacturers can do more with less has also positive consequences on environmental sustainability (Machado, Winroth, and Ribeiro da Silva 2019). For some scholars, given their efficiency improvements, the digital manufacturing transformation is seen as a cost equalizer opportunity to backshore the production of goods (Zhang and Chen 2020; Ancarani, Di Mauro, and Mascali 2019). This transformation is the most suitable in industries in which competition is based on cost, and value proposition is based on the offering of highly customized products packed with sensors and artificial intelligence and capable of performing autonomous tasks. The chief internal barrier for this kind of transformation is complex systems design and management (IB5), i.e., the creation of autonomous production lines which are flexible and resilient at the same time (Kim 2018; Jung et al. 2017).

Digital servitization transformation (III) can be achieved by adopting technological enablers such as big data analytics and resource sharing. This transformation exploits the potential untapped through these enablers of revolutionising the traditional manufacturing paradigm by shifting it to the offering of services through digital products (Chiarini, Belvedere, and Grando 2020; Kohtamäki et al. 2020). The main goal linked to this transformation is that of competitiveness outside the traditional manufacturing sector, that is, the selling of stand-alone products. Manufacturers willing to compete in different business sectors, to reach out to new customer segments, to turn a profit out of product data, and to exploit unexplored revenue models should consider this transformation (Bordeleau, Mosconi, and de Santa-Eulalia 2020; Weking et al. 2020; Schroeder et al. 2019). Since this transformation relies on customers' collaboration, it facilitates closed-loop offerings in which manufacturers engage in the life-long management of their products enabling them to build added-value services on top of this relationship (Rosa et al. 2020; Kohtamäki et al. 2019). Industries in which this transformation is useful are those relevant to servitization, i.e., those in which manufacturers are looking for ways to lock-in customers and stabilize revenue streams (Baines et al. 2017; Cusumano and Kahl 2015; Raddats and Easingwood 2010). The major challenge here is the value proposition redesign (IB16), i.e., the ability to devise new ways to offer value to customers. This challenge is particularly critical because it often comes together with the absence of a customer-oriented culture and with the reluctance of customers to change the way they interact with their providers (Müller et al. 2018; Kiel et al. 2017).

The last quadrant, fully digital transformation (IV), is strictly connected with the other two. This transformation is achieved by adopting the whole spectrum of Industry's 4.0 technological enablers. On the one hand, production routines are enhanced with the latest technologies. On the other hand, entirely new value propositions are developed. This transformation is relevant to manufacturers that need to improve the efficiency of their operations and, at the same time, find new ways to engage with their customers (Sjödin, Parida, Jovanovic, et al. 2020). It can be appropriate for firms offering diverse solutions to different customers at once. For example, firms might find it attractive to digitalize their entire value proposition when their offerings range from pure products to fully-fledged solutions (Kharlamov and Parry 2020; Ambroise et al. 2018). Compared to the other two transformations, this is certainly the most complex to manage. Managers might want to consider a less risky step-by-step approach to this transformation, similar to the case analysed in this study (case B). Rather than going from traditional manufacturing to fully digital manufacturing, company B has first transformed itself into a digital manufacturer, since it felt this transformation more urgent and feasible. Now, it is trying to add a new set of capabilities to its toolbox to offer digital solutions.

Mounting evidence suggests that the manufacturing industry is being digitally transformed and that the final results of this transformation have a positive impact on performance (Abou-foul, Ruiz-Alba, and Soares 2020; Kharlamov and Parry 2020; Queiroz et al. 2020; Lennon Olsen and Tomlin 2019). For traditional manufacturers, the final destinations of their Industry's 4.0 journey are the three business transformations described above. Knowing the technological enablers to arrive there, the goals to achieve, and the barriers to overcome should help managers plan a successful journey to profit from this new industrial paradigm.

Research Implications and Limitations

Industry 4.0 has been conceptualized as a transformative journey and has been broken down into a number of components. A framework and a web application allowing the simulation and the analysis of each possible journey have been built on this conceptualization. These have a number of implications for scholars, managers, and policymakers.

Research Implications. Implications for further research have theoretical, empirical, and methodological sides. On the theoretical side, Industry 4.0 has been interpreted as a transformative journey; and on that basis, its technological enablers, barriers, and goals have been identified and defined. These definitions create a standardized language to classify firms according to their technological level and to discuss Industry's 4.0 barriers and goals. On the empirical side, the relationships in Table 2 derived from the literature review constitute the starting point for both qualitative (investigating 'how' and 'why' such relationships unfold) and quantitative research (investigating these relationships on large-scale datasets). Finally, the web application represents a paradigmatic innovation on the methodological side of managerial research. This 'augmented paper' template enables the interaction between the paper and the readers along new dimensions (in this case, a tailored Industry 4.0 analysis), and can be adopted in analogous research focusing on different topics.

Managerial Implications. From this study, managers can infer both general and specific implications. They should be helped in understanding the many concepts that revolve around Industry 4.0. The transformative journey's conceptualization punctuates the main steps (adoption of technologies, overcoming of barriers, and achievement of goals) of the transformation. The web application provides managers with a tool to interact with the paper's contents. By using the software, the managers will be able to understand how to reach certain goals starting from a number of technological enablers. Along with the explanation of each element provided in the body of the paper, the output of the software will help managers plan their transformative journeys.

Policy Implications. Finally, the external barriers that emerged during the review can be considered from the policy-maker's perspective as a set of priority actions to facilitate the firms' adoption of the Industry's 4.0 paradigm. The barriers (government incentives, regulatory framework, communication standards, infrastructure, and competence shortage) can be divided in two groups, one to be acted upon in the short term and another to be acted upon in the long term. In the short term, policy makers should work on the empowerment of the regulatory framework that guarantees the legal protection of the actors participating in market transactions. Policymakers should also empower and refine the incentives put in place so far to foster the development of the Industry's 4.0 paradigm. In the long term, policy makers should develop programs focused on creating a competitive environment with appropriate resources: an adequate infrastructure for the requirements of Industry's 4.0 data exchange speed and volume, and a proper restructuring of education to meet the challenges required by the Industry's 4.0 job environment. Finally, as a last long-term goal, policy makers should act together to create standards for machine-to-machine communication.

Limitations. Despite the rigorous approach adopted in carrying out this research, some papers may not have been collected. In addition, the relationships upon which the framework is based have come for the most part from empirical case studies. Thus, they have not been tested on a large scale.

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