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I4.0I: A New Way to Rank How Involved a Company Is in the Industry 4.0 Era

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Abstract: Cloud, IoT, big data, and artificial intelligence are currently very present in the industrial and academic areas, being drivers of technological revolution. Such concepts are closely related to Industry 4.0, which can be defined as the idea of a flexible, technological, and connected factory, encompassing the shop floor itself and its relationship between workers, the chain of supply, and final products. Some studies have already been developed to quantify a company's level of maturity within the scope of Industry 4.0. However, there is a lack of a global and unique index that, by receiving as input how many implemented technologies a company has, enables its classification and therefore, comparison with other companies of the same genre. Thus, we present the I4.0I (Industry 4.0 Index), an index that allows companies to measure how far they are in Industry 4.0, enabling competitiveness between factories and stimulating economic and technological growth. To assess the method, companies in the technology sector received and answered a questionnaire in which they marked the technologies they used over the years and the income obtained. The results were used to compare the I4.0I with the profit measured in the same period, proving that the greater the use of technology, the greater the benefits for the company.

Keywords: Industry 4.0; maturity index; smart factory; manufacturing companies; benchmarking

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1. Introduction

The Industry 4.0 (I4.0) concept has been growing during the last years and has become one of the most discussed topics in the industrial and academic fields [1,2]. Many countries have already implemented local programs to improve the development and adoption of the Industry 4.0 methodology. For example, in 2012, the German government launched the initiative called "High-Tech Strategy 2020" [3]; before that, in 2011, the USA introduced the "Advanced Manufacturing Partnership" [4]; in China, the "Made in China 2025" was presented in 2015 [5] and two years earlier, France created "La Nouvelle France Industrielle" [6]. Accordingly, Rupp et al. [7] stated that "the Industry 4.0 paradigm and its technologies are transforming the economy and its production".

The fourth industrial revolution aims to focus on intelligent manufacturing [3], which involves the integration of factory with supply-chain activities, product life cycle [8], and even the workforce [9], through applying digital technologies. With big-data approaches and cyberphysical systems (CPS), it is possible to implement real-time monitoring methods, develop optimization algorithms, and control precisely all devices. Beyond that, the integration, cooperation, and communication between the virtual and real environments can be easily deployed [10]. Overall, multinationals have also structured several optimization initiatives that include business technologies approaches, such as enterprise resource planning (ERP), manufacturing execution systems (MES), and others [11]. Furthermore, it is possible to conclude that factory optimization has a very sophisticated technology architecture. Due to the high precision, control, reliability, and efficiency required by Industry 4.0, the implementation of smart manufacturing is not an easy and inexpensive task.

To be successful in today's competitive environment, manufacturing companies must be able to fabricate high-quality, low-cost products and provide better customer service [12]. Accordingly, manufacturing companies are striving to sustain their specific characteristics of productivity, efficiency, and product quality [13]. While companies' profits are growing marginally, competition is becoming fierce [14] and therefore, those companies that fail to adopt Industry 4.0 will struggle to remain competitive and active on the market.

Some studies have been carried in the field with the intent to assess a manufacturer's capability and measure the maturity and readiness level of a company on implementing smart manufacturing and create road maps [15–23]. However, performance measurements of the Industry 4.0 transformation are still uncertain [24], and none of the models mentioned focus only on the technologies of Industry 4.0 and present all their characteristics. Moreover, there is a lack of a linear, numerical, and more straightforward indicator that classifies each company individually, enabling them to see and understand at what level of Industry 4.0 they are. Furthermore, we envisage that this index must be useful for companies to compare themselves with competitors, creating a more competitive industrial environment, in which all companies constantly seek the highest index to capture customers' attention.

In this context, we analyzed the state of the art, compared relevant solutions already present until January 2023, and separated and described all technologies involved with Industry 4.0. This analysis promoted the creation of a classifying ranking named I4.0I (Industry 4.0 Index). The I4.0I measures the degree of maturity and suitability of a particular company in the context of I4.0 technologies. To evaluate the I4.0I, we developed a questionnaire that was sent to industries in Brazil. Based on the answers, we established how involved a company was in the Industry 4.0 era. The results were passed as feedback to the companies, and final discussions were encouraging, showing our proposal's assertiveness. The contributions of this article are threefold:

- Presenting an overview of the Industry 4.0 technologies, as well as analyzing each one of them and their role in smart manufacturing;
- Allowing companies to measure how many of the I4.0 technologies they had already implemented and to rank them;
- Enabling a better competitiveness between I4.0-driven factories, encouraging economic and technological growth worldwide.

We organized this article as follows: Section 2 shows the related work and open gaps in the literature. In Section 3, we present an overview of the Industry 4.0 concepts and their technologies and submit the methodology used to create the I4.0I index. In Section 4, the evaluation scenarios are presented and in Section 5, a case study is developed. In the sixth (Section 6) section, we present the results and in the seventh (Section 7) section, we show a discussion about the main achievements. Finally, Section 8 reveals the concluding remarks, also highlighting how we addressed the contributions mentioned above.

2. Related Work

As a starting point on constructing the I4.0I, we conducted preliminary research about the status quo of Industry 4.0 maturity models and previously established indexes. We searched a collection of keywords on several research databases, using the following terms: "Industry 4.0 maturity model", "Industry 4.0 maturity level", "Industry 4.0 maturity index", and "Industry 4.0 readiness model". Regarding the data sources, we used the following ones: Google Scholar, ScienceDirect, SpringerLink, Scopus, and IEEE Xplore, filtering those articles that were published from 2015 up to January 2023 in order to obtain recent publications and also a good number of results. In addition, in order to obtain the most cited and recent references, we studied articles that analyzed Industry 4.0 maturity models [25,26].

Rübel et al. [15] developed a maturity model focused mainly on business, processes, and organization, not encompassing the technology area. In addition, we perceived that the construction methodology and maturity levels were not well-explained, lacking details and explanations about the equations. Similarly, in Ganzarain and Errasti [16], the investigators proposed a maturity model to help companies define their goals in Industry 4.0 by analyzing their vision, creating a road map and reaching a final project. In their work, Westermann and Dumitrescu [17] presented a model based mainly on information technologies (more precisely, CPS) and the defining characteristics of a technology for different maturity levels, describing their relationships and the development of a low and high maturity. It was also possible to notice that some of the steps described as CPS levels could be described as different technologies. The main idea of that model was not to seek the highest level of maturity possible but to determine the best and most significant level for each company.

Leyh et al. [18] introduced a maturity model that enabled a company to classify its IT systems' landscape with a focus on Industry 4.0 requirements. Moreover, the recommended activities were shown for each stage of scanning, which allowed a company to reach the next phase of maturity. The analysis result was presented as maturity levels. The DREAMY model [19] divided processes into five categories, not focusing just on technologies. In that model, each process area could be considered a standalone module, so adding or removing one or more spaces was possible if they were not significant in certain industrial situations. It also identified strengths, weaknesses, and growth opportunities and outlined a road map for its digital transformation.

Schumacher et al. [20] presented their results with a radar graph, showing the nine dimensions determined and the level of maturity of a company in each of these dimensions, not giving a single number of classifications. The model embraced factors that were not related to technologies itself, such as the local government. Among all the models researched, the article elaborated by Koska et al. [21] was the only one that presented the results numerically, which were obtained by averaging the values obtained by a questionnaire applied to the analyzed company. However, the paper did not detail the technologies involved with Industry 4.0 and therefore, the survey form was composed of vague answers.

The Industry 4.0 Maturity Index [22] and IMPULS—Industrie 4.0 Readiness [23] were the models found that contained the most detailed methodology and technologies. The former defined four structural areas of the company and six levels of maturity. Then, the company, according to a questionnaire, was classified in one level of maturity for each structural area, resulting in a radar graph. Thus, it was possible to identify the capabilities that required improvement. The model considered some external aspects, such as employees' skills and their openness to change. In the paper written by Lichtblau et al. [23], six dimensions and five maturity levels were established. A company received a questionnaire and based on its answers, was classified according to the lowest score in each dimension; the final level, considering all dimensions' scores, was calculated through a weighted average.

Table 1 summarizes all the works discussed in this section according to the dimensions (items) analyzed by the model to determine the company's maturity level (column 2) and the possible results/levels given (column 3) by the same model. Analyzing it, we observe that none of the models specifically address the technologies involved with the Industry 4.0 concept, such as the Internet of things, artificial intelligence, and cloud computing. Moreover, because many of the current maturity models give their results with a level (not a number), a significant number of companies that do not possess the same technologies and/or resources are classified at the same level. This strategy does not allow companies to analyze their advances over time and compare their technological status against other competitors. Finally, we envisage a gap in presenting a coherent and numerical index (floating-type number) to classify how companies are involved in the Industry 4.0 era to combine company data input, technology descriptions, and a formal benchmarking methodology.

Table 1. Related work overview: existing Industry 4.0 readiness and maturity models.

Model Name [Source]	Dimensions Analyzed by the Model to Determine the Maturity Level	Industry 4.0 Maturity Levels
A Maturity Model for Business Model Management in Industry 4.0 [15]	- Customer segment - Value proposition - Channels - Customer relationship - Source of income - Key resources - Key activities - Key partners - Cost structure	- Implicit - Defined - Validated/standardized - Analyzed - Optimized
Three Stage Maturity Model in SME's Towards Industry 4.0 [16]	The analyzed dimensions are not well-explained	- Initial - Managed - Defined - Transform - Detailed business model
Maturity Model-Based Planning Of Cyber-Physical Systems In The Machinery And Plant Engineering Industry [17]	- Vertical integration - Horizontal integration - Connectivity - Network connection - Security	- Communication and analysis - Interpretation and service - Adaption and optimization - Cooperation
SIMMI 4.0—A Maturity Model for Classifying the Enterprise-wide IT and Software Landscape Focusing on Industry 4.0 [18]	- Vertical integration - Horizontal integration - Digital product development - Cross-sectional technology criteria	- Basic digitization - Cross-departmental digitization - Horizontal and vertical digitization - Full digitization - Optimized full digitization
DREAMY Digital REadiness Assessment MaturitY [19]	- Design and engineering - Production management - Quality management - Maintenance management - Logistics management	- Initial - Managed - Defined - Integrated and interoperable - Digital-oriented
A maturity model for assessing Industry 4.0 readiness and maturity of manufacturing enterprises [20]	- Strategy - Leadership - Customers - Products - Operations - Culture - People - Governance - Technology	Defines five generic levels, where the first level defines a lack of attributes of Industry 4.0 and the last level is the state of the art.
Measuring the Maturity of a Factory for Industry 4.0 [21]	- Product development - Technology - Production management - Production monitoring - Material and inventory - Management of stock - Quality Assurance - Product life cycle management (PLM) - Selection of Toyota production system (TPS) - Green and lean production structure (GALP)	The result is given by a number between 1 and 5, whereby, the bigger the value, bigger is the maturity level.

Table 1. *Cont.*

Model Name [Source]	Dimensions Analyzed by the Model to Determine the Maturity Level	Industry 4.0 Maturity Levels
Industrie 4.0 Maturity Index (Acatech Study) [22]	- Resources - Information systems - Culture - Organizational structure	- Computerization - Connectivity - Visibility - Transparency - Predictive capacity - Adaptability
IMPULS—Industrie 4.0 Readiness [23]	- Employees - Strategy and organization - Smart factory - Smart operations - Smart products - Data-driven services	- Outsider - Beginner - Intermediate - Experienced - Expert - Top performer

3. I4.0I Proposal—Industry 4.0 Index

This section presents the methodology used to create the Industry 4.0 Index. For that purpose, we divided the section into three subsections. The first one presents previous research about the Industry 4.0's concept and technologies; the second one describes the design decisions, and the third one shows all steps taken to establish the I4.0I.

3.1. Industry 4.0 Technologies: An Overview

The Industry 4.0 concept was first presented in Germany as a prediction of the industrial future [3]. Since then, some authors have already called I4.0 *the fourth industrial revolution*. While the use of the steam engine marked the first industrial revolution, electrical power marked the second and electronics marked the third [27], this one refers to "the digitization of the real world, applied to the productive processes, by transforming the traditional way into an interconnected world, including suppliers and customers, to obtain an intelligent product" [28]. Although many authors have already studied the Industry 4.0 concept, in our paper, we use the list of innovations presented by Frank et al. [10].

In their paper, the researchers analyzed 92 manufacturing companies to investigate the implementation of Industry 4.0 technologies. Before performing the investigation itself, the researchers studied, separated, and divided all technologies into two main layers, which they called: *base technologies* and *front-end technologies*, where the former refers to technologies that provide intelligence and connectivity for the second, while the latter comprehends rising technologies in the manufacturing area (what the authors call *smart manufacturing*) and the new way that products are offered (*smart products*). The so-called front-end technologies also consider the technologies used to improve the communication between the factory, suppliers, and customers (*smart supply chain*) and the those related to the way workers to do their jobs (*smart working*).

In our paper, we studied and summarized all the technologies related to the Industry 4.0 concept in Table 2. Moreover, to clarify the categorization, we removed the classification into two main layers (front-end technologies and base technologies) used by Frank et al. [10] and maintained the subcategories, classifying what the authors [10] called base technologies as *communication technologies*. In Figure 1, we represent a framework of the correlation between the categories of Industry 4.0 technologies. Because it is related to connecting other companies' units, suppliers, and customers to the factory, the smart supply chain comes, chronologically, before production, which includes smart manufacturing and smart working. Since they are connected to final products, smart products appear later, and communication technologies connect everything all together. Finally, the market receives the sum of all technologies.

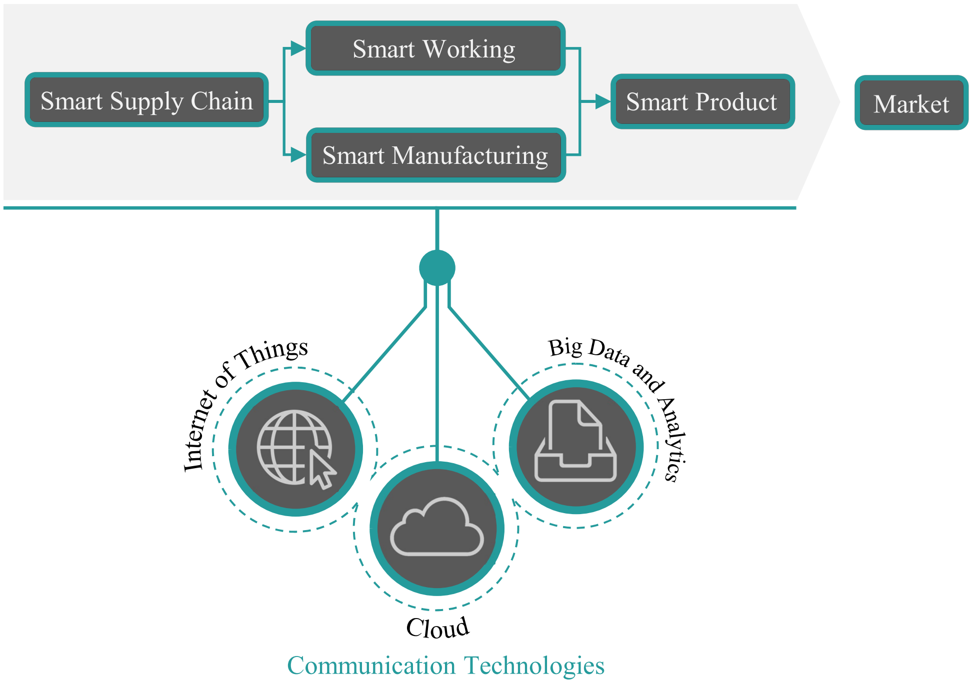


Figure 1. Framework representing the flow and correlation between the categories of Industry 4.0 Technologies.

3.2. Design Decisions

As discussed in Section 2, none of the current maturity models address specifically the technologies involved with the Industry 4.0 concept. In addition, the strategy of classifying companies in levels does not allow them to both analyze their advances over time and to compare their technological status against other competitors. Consequently, it is possible to picture a lack of a coherent and numerical index that classifies how companies are inserted in the Industry 4.0 era. With this in mind and aiming to allow companies to compare their technological status, we present the I4.0I.

Regarding Industry 4.0, we understand the I4.0 index of a company as a number that identifies and quantifies how involved it is in the fourth industrial revolution, when considering the technologies described in Table 2. We stress that our paper is focused on ranking companies according to their technologies and therefore, we do not consider organizational and cultural factors, for example. It is also essential to point out that, in order to compare results and use the index as a benchmark reference, the I4.0I must be used by companies related to the same industry. Moreover, so that the comparison is fair, it would be ideal if the I4.0I was used to compare companies with similar sizes.

Before being able to present a numerical value to the I4.0I, it was necessary to separate all technologies into ten levels, according to their technological and implementation status, so that the less technical and more implemented were positioned at level 1 and the most technological (less implemented) were positioned at level 10. Afterward, the technologies were compared inside each level, creating a subranking, and each one received a value related to its classification. The sum of the values related to the technologies currently used by the referred company gave the I4.0I. Figure 2 presents a block diagram of the methodology used to obtain the I4.0I. In the following subsection, each step is elucidated.

Table 2. Industry 4.0 technologies

Category	Technology (Source)	Description
Smart manufacturing	Sensors [22,29]	Device that detects or measures a physical property and registers, indicates, or responds to it.
	Actuators [22,29]	Device that transforms a control signal (electrical) into a mechanical action.
	Programmable logic controllers (PLC) [22,29]	Robust computers used for industrial automation, which automate a specific process, function or production line.
	Supervisory control and data acquisition (SCADA) [10,30,31]	System for collecting and analyzing data in real time used to monitor and control a plant or equipment in industries.
	Manufacturing execution systems (MES) [10,30,31]	Set of tools (software and hardware) that confront what was planned and what is actually being executed.
	Enterprise resource planning (ERP) [8]	Software platform developed to interconnect several departments of a company, enabling the automation and storage of all information.
	Energy monitoring [3,32]	Hardware and software that connect to energy resources to provide information on energy consumption.
	Energy improvement [3,33]	Use of data obtained at the factory to improve energy consumption through intelligent systems.
	Traceability of final products [8,10]	Possibility to track finished products inside and outside the factory by placing sensors.
	Traceability of raw materials [10]	Possibility to track raw materials inside and outside the factory by placing sensors.
	Automatic nonconformities identification [10,34]	Automatic identification of nonconformities in production.
	Industrial robots [32]	Use of automatic and reprogrammable robots in manufacturing systems.
	Machine-to-machine (M2M) communication [32]	Wired or wireless network configuration that allows devices of the same type and capacity to communicate and self-organize freely.
	AI for production [32]	Artificial intelligence techniques applied to the improvement of production and assistance in considering last minute orders.
	AI for maintenance [35]	Artificial intelligence techniques used to predict and diagnose failures, classifying the type and recommending maintenance actions.
	Virtual commissioning [36]	Using a virtual plant model and real PLCs, it allows a complete simulation of manufacturing processes for authentication.

Table 2. *Cont.*

Category	Technology (Source)	Description
Additive manufacturing [37]	It allows product customization using digital models and 3D printing without major manufacturing penalties.	
Smart products	Flexible lines [8]	Reconfigurable manufacturing, where machines self-organize and adapt to different types of products.
	Passive smart products [38]	Products capable of monitoring their condition and reporting to the company.
	Active smart products [38]	Products with self-optimization capabilities based on data acquisition and remote-control capabilities.
	Autonomous smart products [38]	Products that learn, adapt, and operate on their own.
Smart working	Remote monitoring [34]	It allows workers to monitor production, see problems, and give instructions even when outside the factory.
	Collaborative robots [34]	Use of robots capable of interacting with human beings, assisting them in manufacturing.
Smart working	Remote operation [34]	Ability to operate a system or machines remotely.
	Augmented reality [39,40]	Use of virtual objects layers in a real environment to aid in maintenance and training.
	Virtual reality [39,40]	Use of a totally virtual environment to aid in maintenance and training.
Smart supply chain	Digital platform with other companies' units [10,41]	Use of an electronic form for interaction and exchange of materials between the company and its other units.
	Digital platform with suppliers [10,41]	Use of an electronic means for interaction and exchange of materials between the company and its suppliers.
	Digital platform with customers [10,41]	Use of an electronic means for interaction and exchange of materials between the company and its customers.
Communication technologies	Internet of things (IoT) [35]	Wireless interconnection of devices (sensors) via the internet, allowing them to receive and send data.
	Cloud [35,42]	Internet service provider that can be accessed remotely, facilitating the integration of different devices and easy information sharing.
	Big data and analytics [38,43]	Use of advanced analytical techniques on very large and diverse data sets.

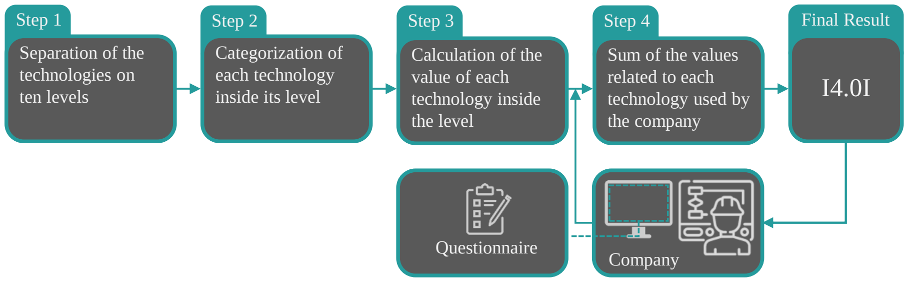


Figure 2. High level abstraction of our paper's block diagram.

3.3. Methodology

This study aimed to rank a company according to how involved it was in the Industry 4.0 era when it came to the technologies related to it. As previously stated, to do that, it was first necessary to rank all technologies cited in Table 2. We based our ranking proposal on the paper presented by Frank et al. [10], where the authors investigated 92 manufacturing companies to study the implementation of the technologies related to the concept of Industry 4.0. By the end of the study, the researchers exhibited a framework that contained a summary of Industry 4.0's adoption patterns, organizing the technologies in categories and then ranking them horizontally, in levels of complexity, creating a two-dimensional framework. However, it dod not present a classification of each technology separately and moreover, the framework did not have a vertical leveling.

3.3.1. Step 1: Categorization of the Technologies in Levels

Frank et al. [10] ensured that smart manufacturing had a central role in Industry 4.0, which was strongly related to the implementation of smart products. The same authors [10] concluded that, although little implemented, as smart manufacturing gets consolidated, the use of technologies to support a smart supply chain and smart working, which complement smart manufacturing, must rise. Moreover, among the technologies mentioned in Table 2, flexible lines are the only technology that did not have a robust implementation in any of the categories of companies surveyed.

While Frank et al. [10] presented a two-dimensional framework of the Industry 4.0 technologies, we created a vertical ranking of these technologies by studying the article cited, the statements made, and the data tables presented by the authors. Moreover, a dependency of some technologies on others was noticed. After making these analyses, we were able to scale all 32 technologies on ten different levels, from less to more technological.

3.3.2. Step 2: Ranking Each Technology Inside Its Level

Up to this point, we have explained how we separated the technologies presented in Table 2 into ten different levels, based on the statements and data collected by Frank et al. [10]. Proceeding with the creation of the I4.0I, each technology was classified within its level. To quantify each technology's technological level compared to others of the same level, we needed to use objective criteria to validate the study. We selected some characteristics to search: the expected market investment, time on the market, number of people involved to create the technology, how much benefit the technology brought, and how much time it took to develop the technology and logical analysis.

From the criteria cited above, we found more results, with reliable sources, in three of them: the expected market investment, time on the market, and the logical analysis—if a technology depended on another to function, for example, [24,44–50]. A review of articles, company reports, news, and expert consultations was conducted to obtain this information, and as a result, we classified the technologies according to these criteria. Table 3 presents a generic example of this step, where technologies A, B, C, and D represent any technology cited in Table 2 and the years when these technologies were implemented are represented, chronologically, by a sequence of letters, where CCCC > BBBB > AAAA.

Table 3. Generic example of the assignment of n values.

L	n_L	Technology	Expected Market Investment	Time on the Market	Logical Analysis
3	2	Technology A	There is not enough information	Since BBBB	Technology A is required to obtain technology D.
	4	Technology B	B's profit > C's profit	Since CCCC	No requirements.
	3	Technology C	C's profit < B's profit	Since AAAA	No requirements.
	1	Technology D	There is not enough information	There is not enough information	To obtain technology D, it is necessary to have technology A.

3.3.3. Step 3: Computing Each Technology's Value

To limit the value of the index between 0 and 10, with 0 being the lowest value and 10 the highest value, each technology was weighted using Equation (1), where:

- L = technology's level;
- n_L: position of the technology inside its own level;
- $W_{n,L}$: technology's truth value related to its n number;
- N_L: total number of technologies on the respective level;
- T_L: calculated by Equation (2), it allows the $W_{n,L}$ to represent the truth value of each technology.

$$W_{n,L} = \frac{n_L/N_L}{T_L} \quad (1)$$

$$T_L = \sum_{n_L=1}^{N_L} \frac{n_L}{N_L} \quad (2)$$

As an example, we show the calculation of the truth value related to each generic technology presented in Table 3, where it is possible to see that the respective level is composed of four technologies, which gives the N_L number. Hence, using Equation (2), we can calculate T_L to this general level:

$$T_L = \sum_{n_L=1}^{4} \frac{n_L}{N_L} = \frac{1}{4} + \frac{2}{4} + \frac{3}{4} + \frac{4}{4}$$

$$T_L = 2.5$$

Replacing the T_L value calculated above in Equation (1), we can determine the $W_{n,L}$ related to each technology.

- Technology A:

$$W_{2,3} = \frac{2/4}{2.5}$$

$$W_{2,3} = 0.2$$

- Technology B:

$$W_{4,3} = \frac{4/4}{2.5}$$

$$W_{4,3} = 0.4$$

- Technology C:

$$W_{3,3} = \frac{3/4}{2.5}$$

$$W_{3,3} = 0.3$$

- Technology D:

$$W_{1,3} = \frac{1/4}{2.5}$$

$$W_{1,3} = 0.1$$

As we can see, the sum of all $W_{n,L}$ values calculated above results in 1. Thus, considering ten levels, the maximum index will be represented by the number 10 (when the company uses all technologies related to Industry 4.0), and the minimum index will be represented by the number 0 (when the company does not use any of the technologies cited in Table 2).

After computations, we can present Table 4, which consists of a complete and reorganized Table 3. Table 5 shows all technologies ranked with their respective L, n_L, and $W_{n,L}$ values. It is important to stress that the $W_{n,L}$ values are limited to a representation with just two decimal places; however, as the sum of all values at each level must result in 1, all necessary decimal places must be considered in the calculation.

Table 4. Generic example of the assignment of n values with the respective $W_{n,L}$ calculated value.

L	n_L	Technology	Expected Market Investment	Time on the Market	Logical Analysis	$W_{n,L}$
3	1	Technology D	There is not enough information.	There is not enough information.	To obtain technology D, it is necessary to have technology A.	0.1
	2	Technology A	There is not enough information.	Since BBBB	Technology A is required to obtain technology D.	0.2
	3	Technology C	C's profit < B's profit	Since AAAA	No requirements.	0.3
	4	Technology B	B's profit > C's profit	Since CCCC	No requirements.	0.4

Table 5. Calculated $W_{n,L}$ values related to each technology

L	n_L	Technology	$W_{n,L}$
1	1	Sensors	0.05
	2	Actuators	0.10
	3	PLC	0.14
	4	SCADA	0.19
	5	MES	0.24
	6	ERP	0.29
2	1	Energy monitoring	0.10
	2	Energy improvement	0.20
	3	Remote monitoring	0.30
	4	Internet of things	0.40
3	1	Traceability of final products	0.17
	2	Passive smart products	0.33
	3	Cloud	0.50
4	1	Digital platform with other companies' units	0.33
	2	Traceability of raw materials	0.67

Table 5. *Cont.*

L	n_L	Technology	$W_{n,L}$
5	1	Automatic nonconformities identification	0.07
	2	Collaborative robots	0.13
	3	M2M communication	0.20
	4	Industrial robots	0.27
	5	Big data and analytics	0.33
6	1	AI for production	0.10
	2	AI for maintenance	0.20
	3	Virtual commissioning	0.30
	4	Active smart products	0.40
7	1	Digital platform with suppliers	0.33
	2	Remote operation	0.67
8	1	Autonomous smart products	1.00
9	1	Digital platform with customers	0.17
	2	Virtual reality	0.33
	3	Augmented reality	0.50
10	1	Additive manufacturing	0.33
	2	Flexible lines	0.67

3.3.4. Step 4: Generating the Final Value for I4.0I

Finally, the I4.0I was obtained by a sum of the $W_{n,L}$ value related to each technology used by the company. According to [51], the need for companies to join the era of digitalization is emerging and the indicator presented in this article can be used to foster competitiveness among I4.0-driven factories, encourage economic and technological growth worldwide, and also to help enterprises remain competitive, change, and adapt to the changing landscape. As it is an easily computed index, it can be updated frequently. To obtain the needed information from companies to provide the I4.0I, we developed a questionnaire.

4. Modeling the Experiments

This section describes the methods used to analyze, evaluate, and test the usage of the I4.0I. It is important to stress that because this paper proposes a new way of ranking companies, promoting comparison and benchmarking, it is not possible to compare the obtained results with other methods to determine whether the results are correct. Therefore, we performed an evaluation method based on the profit gained by companies with the increasing use of Industry 4.0 technologies. Using this method, it is also possible to analyze the growth and compare the I4.0I obtained between companies from the same industry.

As previously stated, the information required to calculate a company's I4.0I was obtained through a questionnaire. The survey's principal idea was to be able to characterize each company according to the use of the technologies cited in Table 2, relating it to the profit obtained and expected in three different periods. With a sum of the $W_{n,L}$ of each technology marked, we were able to calculate the I4.0I of a company each year and afterwards relate it to the profit obtained. It is important to note that before sending the questionnaires, we were careful to select companies that had not been economically harmed by external factors, in other words, companies whose growth planning had been accomplished.

Figure 3 exhibits an example of the questions present in the questionnaire, where the manager had to mark if the company used the particular technology each year (if the technology was not used, it was not necessary to mark anything). This process was repeated for all technologies presented in Table 2. The questionnaire also contained questions referring to the company's profit in each period and in order to avoid asking for confidential or sensitive information, we determined the first year as one and asked the representatives to quantify the next year's profit as a multiplicative of that number.

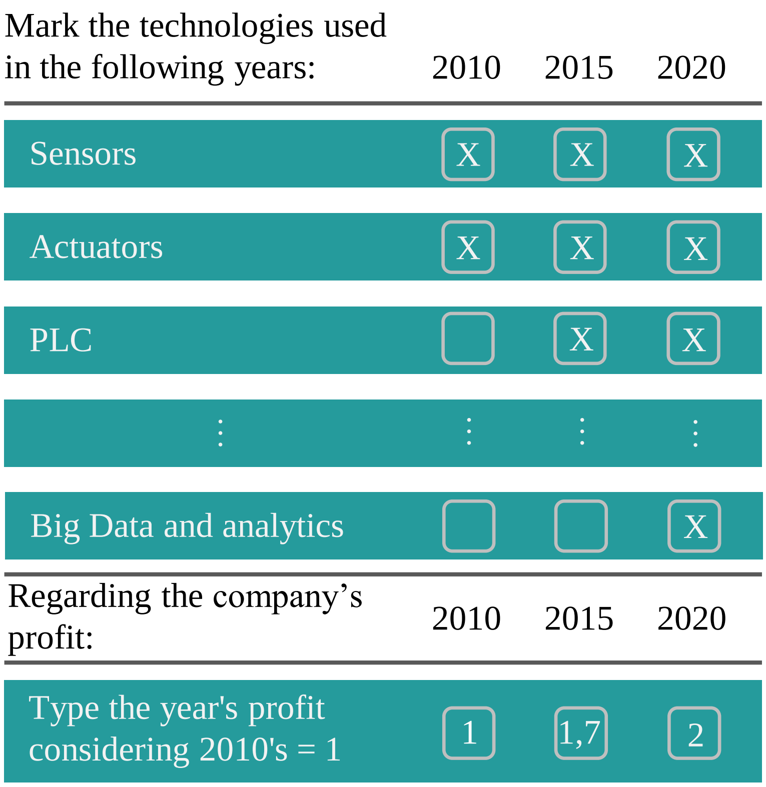


Figure 3. Exemplary questions and possible answers to the questionnaire applied.

It is important to stress that in order for the questionnaire to be appropriately answered ans so that there were no doubts about relevant concepts, a definition of each technology was added. Moreover, if the respondent did not feel qualified to answer all or some of the questions, they could tell us that, leaving the answer blank.

We were able to calculate the companies' I4.0I for each period with the information on which technologies were used each year. These numbers were then compared to the referred income, making it possible to generate a graphic of comparison between the year's income and the year's I4.0I. The calculated index could also be represented by a radar graph, where the total number was divided into ten different levels. Hence, the evolution over time and how it impacted the final result were better seen.

To numerically associate the company's profit to its I4.0I, we related the values obtained by calculating and comparing the growth rates of these values over time. Assuming that the data from the third year represented the maximum value (100%), the previous years' I4.0I and profit represented a portion of the total. Hence, the growth rate of a particular period was given by the difference between the data from two different years, as shown by the equations below, where the years are represented chronologically by the numbers one, two, and three.

- Profit's growth rates (*PGR*):

$$PGR_{2-1} = \frac{P_2}{P_3} \times 100 - \frac{P_1}{P_3} \times 100 \quad (3)$$

$$PGR_{3-2} = \frac{P_3}{P_3} \times 100 - \frac{P_2}{P_3} \times 100 \quad (4)$$

- I4.0I's growth rates (IGR):

$$IGR_{2-1} = \frac{I_2}{I_3} \times 100 - \frac{I_1}{I_3} \times 100 \quad (5)$$

$$IGR_{3-2} = \frac{I_3}{I_3} \times 100 - \frac{I_2}{I_3} \times 100 \quad (6)$$

In Figure 4, we present a complete block diagram of the paper's methodology and evaluation, expanding and deepening what is shown in Figure 2. The years used in the questionnaire to evaluate the usage of the I4.0I are generically and chronologically represented in the figure by the numbers one, two, and three. The final number given by I4.0I can be used by the company to rank and compare its current technological status to other companies' of the same industry, allowing competitiveness and creating benchmarks.

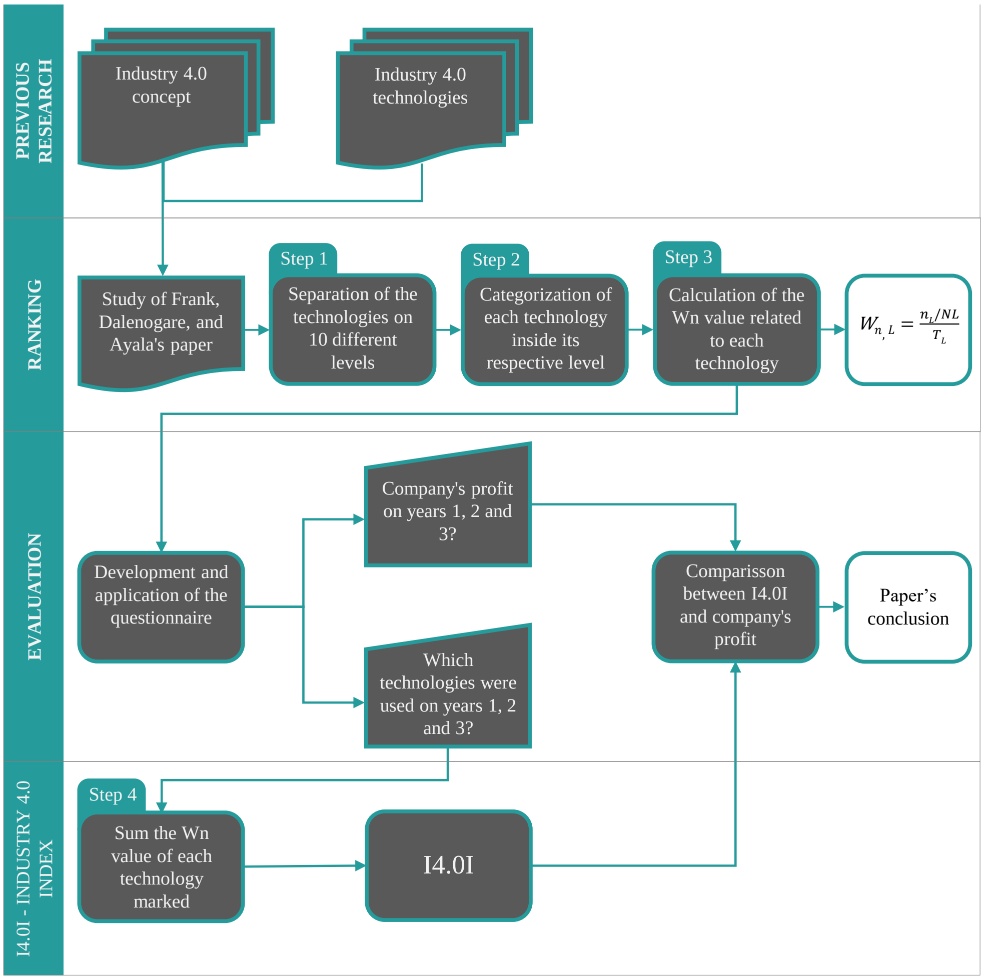


Figure 4. Low-level abstraction of our paper's block diagram.

5. Case Study

In this section, we present a case study of the created index by applying the methods described in the previous sections in a company, here called Company A to preserve its image. We start by exhibiting the results obtained from the questionnaire sent to that company, which are represented in Table 6.

Table 6. Company A's questionnaire results

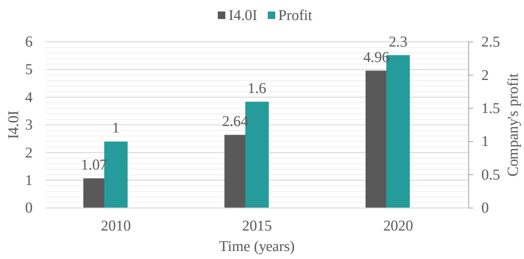
Mark the technologies used in the following years:			
Technology	**2010**	**2015**	**2020**
Sensors	X	X	X
Actuators	X	X	X
Programmable logic controllers (PLC)	X	X	X
Supervisory control and data acquisition (SCADA)			X
Manufacturing execution systems (MES)			
Enterprise resource planning (ERP)	X	X	X
Energy monitoring Energy improvement			
Traceability of final products			
Traceability of raw materials			
Automatic nonconformities identification			
Industrial Robots		X	X
Machine-to-machine (M2M) communication		X	X
AI for production			
AI for maintenance			
Virtual commissioning			
Additive manufacturing			
Flexible lines		X	X
Passive smart products		X	X
Active smart products			X
Autonomous smart products			X
Remote monitoring			
Collaborative robots			
Remote operation			
Augmented reality			
Virtual reality			
Digital platform with other companies' units			X
Digital platform with suppliers			
Digital platform with customers			
Technology	**2010**	**2015**	**2020**
Internet of things (IoT)			X
Cloud	X	X	X
Big data and analytics			
Regarding the company's profit:	**2010**	**2015**	**2020**
Type the year's profit considering 2010 = 1	1	1.6	2.3

Using these answers and the values presented in Table 3, we calculated the I4.0I related to each year by summing all $W_{n,L}$ values related to the technologies marked and afterward, we generated a comparison table between the results obtained and the profits' data given by the company (Table 7).

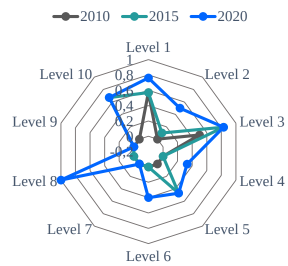
Table 7. Company A's calculated I4.0I and profit comparison.

	2010	2015	2020
I4.0I	1.07	2.64	4.96
Profit	1	1.6	2.3

The table above resulted in a graph showing the evolution of Company A's earnings and I4.0I over time (Figure 5a). To better understand this evolution, we also represented the data collected by the questionnaire with a radar chart, where the final number was divided by its ten levels. This way, the company could see which levels contributed the most to its ranking. In addition, by including data from three different years, we could better represent how the index evolved in that period, showing the increase in investments at each level (Figure 5b).



(**a**) Company A's bar chart



(**b**) Company A's radar chart

Figure 5. Company A's graphics generated by the answers obtained by the questionnaire applied.

Using the data from company A on Equations (3)–(6) to exemplify the numerical evaluation, we obtained the following:

- Profit's growth rates (PGR):

$$PGR_{2015-2010} = 69.57\% - 43.48\% = 26.09\%$$

$$PGR_{2020-2015} = 100\% - 69.57\% = 30.43\%$$

- I4.0I's growth rates (IGR):

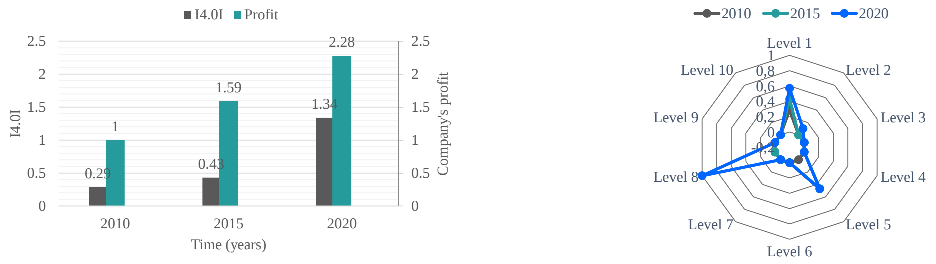
$$IGR_{2015-2010} = 53.23\% - 21.57\% = 31.66\%$$

$$IGR_{2020-2015} = 100\% - 53.23\% = 46.77\%$$

Analyzing the results, we can see that Company A's $IGR_{2015–2010}$ and $PGR_{2015–2010}$ were very similar, presenting a range of approximately ±5%. When we analyzed the company's $IGR_{2020–2015}$ and $PGR_{2020–2015}$, we saw that the company's I4.0I grew about 16% faster than its profit.

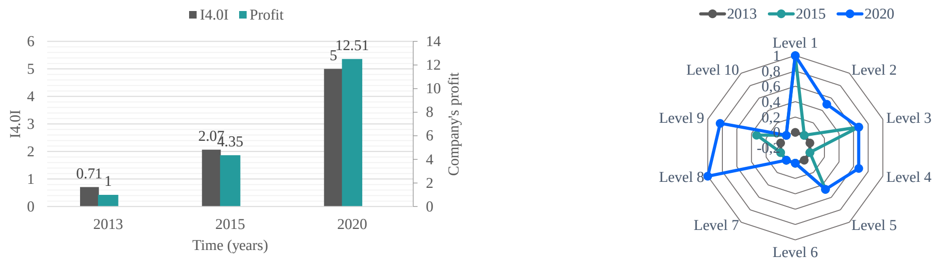
6. Results

As previously stated, we used a questionnaire to obtain information about the companies' technologies in three different years and hence calculated the periods' respective Industry 4.0 Index. Company A's analysis was shown in Section 5 and in this section, we describe and discuss the results obtained when we applied all processes presented in the previous section to two other companies, here called Company B and Company C, to preserve their images. After analyzing Company B and Company C's questionnaires, we could compute their income and I4.0I evolution over time, as well as generating bar and radar charts (Figures 6 and 7).



(**a**) Company B's bar chart (**b**) Company B's radar chart

Figure 6. Company B's graphics generated by the answers obtained by the questionnaire applied.



(**a**) Company C's bar chart (**b**) Company C's radar chart

Figure 7. Company C's graphics generated by the answers obtained by the questionnaire applied.

When we analyzed the graphics presented, it was possible to verify that Company C's graphic (Figure 7) started in a different year compared to the other companies. This happened because the referred company only started producing in 2013. Despite that, the analysis remained the same.

On the radar charts, we can see different facets of a company's performance, represented by the ten levels. For each facet, there were minimum thresholds that each company had to achieve to be competitive in its respective field. Such thresholds would be automatically calculated from the results of other similar companies that also computed their I4.0I. At the end of the index determination, the global index was given to the company, together with the facets whose threshold it did not reach.

Using the data from companies B and C in Equations (3)–(6) to obtain a numerical analysis, it is possible to see that:

- With Company B's data, the $IGR_{2015–2010}$ was smaller than the $PGR_{2015–2010}$, but in the next five years, the I4.0I grew at a rate of about 38% faster than the profit.
- Company C's I4.0I growth rates were approximately the same as the profits in all periods analyzed, with a range of ±5%.

7. Discussion

Looking for a direct relationship between a company's profit and its I4.0I is complicated and involves several subjective variables. Therefore, this situation is beyond what is humanly understandable, and finding a constant proportion ratio between both variables would be meaningless. However, when observing the graphics presented in Section 5, it becomes evident that in all situations, the companies' profit grows as companies become more involved in Industry 4.0, and our proposal captured that. Moreover, this observation demonstrated that there was a correlation between the I4.0I and company growth, even if it contained an inconstant discrepancy. When investing in technology, a company gains productivity, quality, flexibility, and speed, reflecting on its final profit and a better I4.0I.

We envisage that the proposed benchmark could be seen as an indicator with a direct impact on the market. Here, for example, we can remember the case of ISO 9000 launched in 1987, presenting a set of standards within the scope of quality management systems.

When it was launched, it caused a rush for companies to adapt themselves; otherwise, they would not be seen as competitive/organized by the market [52]. In this scope, we can picture I4.0I as the new required standard compliance in the I4.0 era, where companies could be classified in levels (A, B, or C, and so on) following their achieved I4.0I score. Finally, we understand that we are promoting a unified index to the community, boosting the adoption of technologies and market competitiveness.

We understand that it is risky to conclude anything because we could only obtain data from three different companies. However, we envisage future work focused on obtaining more data and improving data acquisition and analysis, creating, for example, a web page where companies can access information about I4.0 and its technologies and get to know the I4.0I and calculate its index. We also understand that technologies evolve and degrade over time. Thus, future work would also be focused on developing a value related to time degradation, responsible for keeping the truth values updated.

8. Conclusions

After separating and classifying the technologies involved in the so-called fourth industrial revolution, we added to the literature an index named I4.0I, which was based on a classification of technology developed at ten different levels. The final I4.0I was given by the sum of the truth values related to the technologies used by the company.

To test the method created, we designed a questionnaire delivered to manufacturing companies that should mark the technologies used in three different periods, the income obtained in each observation stage, and select their field of activity. The information collected was used to generate graphs related to both variables over time and a radar graph of the evolution of I4.0I over time.

The companies' earnings' growth rates and I4.0I over time were used to relate the two variables numerically. These evaluations confirmed a correlation between the companies' I4.0I and their profits, justifying the use of the created index. The number provided can be used to inform companies about their level of involvement in Industry 4.0, guide them on the next steps, and enable competitiveness between factories, stimulating economic and technological growth.

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