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Proposal and Validation of an Industry 4.0 Maturity Model for SMEs

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Abstract:

Purpose: This paper seeks to establish an Industry 4.0 maturity model for manufacturing SMEs. This research presents the characteristics of the proposed model, which takes the elements and the scope of the fourth industrial revolution, as well as the dimensions and assessment scales of some maturity models already applied. Likewise, this document shows the modelling process and the model's validation in SMEs in the city of Bogotá-Colombia.

Design/methodology/approach: To determine the criteria of the maturity model, 6 major stages have been established: Literature Review, Development of the model; Validation of the model; Application of the model; Data analysis; and Conclusion and Recommendations.

Findings: Considering the validation of some maturity models shown in the literature review, and aligned with the purpose of this article, 8 dimensions have been established to measure the maturity level of SMEs: Service; Operations; Quality; Products; Documented information- Big Data; Leadership and strategy; Communication; and Culture and people. A model has been generated that allows evaluating the degree of compliance in each dimension for manufacturing SMEs. The model can be applicable to companies in any industry. Also, it can determine the degree of implementation compliance of companies in the same sector.

Research limitations/implications: According to the literature reviewed, SMEs, especially those in Latin America, still do not have a culture of applying the elements of Industry 4.0. Therefore, in the research, it was not easy to understand the intrinsic variables of Industry 4.0 that SMEs have applied in different areas, which does not allow us to have the current context of SMEs and from that perspective to have a better simulation of the business model maturity.

Practical implications: The model presented in this document serves as a basis for SMEs in Latin America to establish a baseline measurement in relation to the application of Industry 4.0 elements in companies.

Social implications: What is intended with this work is to frame a baseline so that companies can understand their current maturity level in the terms that industry 4.0 could cover. Likewise, they can generate actions for the appropriation of new technologies that allow them to be more competitive. This document can be taken and applied by those entrepreneurs companies who wish to measure their operations.

Originality/value: The essential point for the generation of the maturity level measurement model is focused on determining the necessary dimensions on which the evaluation is based. In the literature found, most models focus their dimensions on measuring the digital in their processes and tangentially evaluate the organizational structure and the relationship between them. Additionally, the authors who address the organization as a whole do not reveal the details for SMEs to self-evaluate. The models found have only been implemented to evaluate one company along or individually. This model presents the core dimensions holistically and explicitly, taking important criteria such as quality, service, communication, and the culture of all employees. Additionally, it shows in detail the model that allows to SMEs of the manufacturing sector to self-assess themselves in each dimension and in turn the degree of the business sector in which they are or belong.

Keywords: industry 4.0, maturity models, manufacturing, Small and Medium Enterprises (SMEs)

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1. Introduction

Industry 4.0 is focused on companies developing facilities with manufacturing and storage systems capable of exchanging information autonomously, triggering actions and applying control independently (Flores, Li, Chen, Zhan, Zhang & Chen, 2015). The cited above, It would include making improvements in the processes involved in the operations of manufacturing, engineering, use of materials, and life cycle management, in which an important part is to generate permanent traceability of the products from the moment of the order to outbound logistics to the customer (Kagermann, Helbig, Hellinger & Wahlster, 2013). Some organizations are becoming aware of the importance of integrating the vision and understanding of Industry 4.0 in their organizational culture and productive systems (Ganzarain & Errasti, 2016). In this sense, SMEs must comply with global standards of quality, technology, sustainability, and prices. However, SMEs cannot compete in global markets due to their technological deficiencies and lack of sustainability in operations (Singh & Kumar, 2020). In addition, due to the scope and complexity of the Industry 4.0 concept, the understanding of the adoption of its components, processes are lagging behind among manufacturing companies (Kainer, 2017).

SMEs tend to be less informed about Industry 4.0 concepts. Therefore, an evaluation model must clearly define the concepts and technologies offered by this Industry (Rauch, Unterhofer, Rojas, Gualtieri, Woschank & Matt, 2020). A maturity model is a useful tool that allows companies and organizations to be evaluated, in the same way, it allows to illustrate the path that is still needed to achieve, in a more structured and organized way, the fulfillment of the planned objectives (Pöppelbuß & Röglinger, 2011).

Although the literature shows some Industry 4.0 maturity models, it is observed that the major part of they are established to evaluate large companies, they do not present a perspective from SMEs requirements (Mittal, Romero & Wuest, 2018). In this sense, some authors have started establishing maturity models applied to SMEs. However, they do not present the characterization and detail that can serve them as a free tool that can be appropriate in each of their sectors.

According to the growing need of SMEs to integrate Industry 4.0 into their operational and administrative processes, and the difficulties they have to face the challenges that implementation entails in that sense. It is necessary to create methods, models, strategies and / or tools that serve as a simplified guide to companies for appropriation throughout the supply chain and / or supplies (Ravinder, Rajesh, Singh & Dwivedi, 2020).

As the main specific objective of this research are related with: 1) To synthetize the state of art about the semantic of industry 4.0; 2) To study the current and diverse literature about maturity models considering dimensions of industry 4.0; 3) To select a referential maturity models to be updated with industry 4.0 dimensions under SMEs perspective; 4) To improve the referential maturity model for SMEs from some local industries around Bogotá city;

and 5) To apply a survey of this updated model to these selected SMEs to verify the functionality and check the correct fitness.

This research presents, in a detailed and explicit way, an Industry 4.0 maturity model for manufacturing SMEs, which shows the elements and scope of the fourth industrial revolution, as well as the dimensions and evaluation scales of some maturity models already applied. It is of particular interest to illustrate how to apply the maturity model, considering the group capacity of SMEs, by incorporating the dimensions of Industry 4.0. Likewise, this document shows the process of modeling and validation of the model in SMEs of the city of Bogotá - Colombia.

2. Elements, Scopes of Industry 4.0 and Maturity Models

This section allows to visualize the unified characteristics of industry 4.0 and Smart Manufacturing as trends that outline the fourth industrial revolution; in this sense, the different elements that integrate it are presented, in addition to the scope or approaches that both plans in its application. All this as a basis for evaluating the maturity levels of SMEs.

2.1. The Main Industry 4.0 Characteristics

The world is changing towards a new industry whose immersion in innovation, embedded systems, manufacturing automatiation, and artificial intelligence has configured a new era called industry 4.0 or fourth industrial revolution. The industry 4.0 is a key initiative that rises in Germany and contains a technical strategy to achieve a Smart Manufacturing System (SMS), based on the creation of innovations that include smart products, smart production systems, smart factories, and smart logistics that work in a decentralized and dynamic way. (Lu, Morris & Frechette, 2016). On the other hand, while the German government promotes the computerization of manufacturing industries with the Industrial 4.0 program, the United States generates intelligent manufacturing initiatives, named as Smart Manufacturing. This Smart Manufacturing initiative was promoted by Smart Manufacturing Leadership Coalition (SMLC) in 2011 (Thoben, Wiesner & Wuest, 2017), which developed a business roadmap to develop and implement Smart Manufacturing capabilities that will enable the performance and competitiveness of the next generation of economy, energy, sustainability, environment, health, and safety (Smart Manufacturing Leadership Coalition, 2011).

Industry 4.0 is determined by the application of information technology in the processes present in organizations (process-based approach). Information and communications technology are experiencing a sudden development in which many technologies have emerged, such as cloud computing, the Internet of things, big data, process integration, simulations, and artificial intelligence. These new technological advances are penetrating the manufacturing industry allowing the fusion of physical and virtual spaces through Cyber-Physical Systems (CPS). With the help of the Internet, CPS in Industry 4.0, leads to the so-called Internet of Things (IoT) and Internet of services (IoS) (Zheng, Wang, Sang & Zhong, 2018).

The topics mentioned in the Industry 4.0 environment mapping are: Cloud-based big data analytics, Enterprise Resource Planning (ERP), Machine Learning, Manufacturing Execution Systems (MES), IoT, The Wireless Sensor Network (WSN), Virtual Reality (VR) and augmented reality (AR), Human-Machine Interface (HMI), simulation, among others (Elkaseer, Ali, Scholz & Salama, 2018). Hermann, Pentek and Otto (2016), established some terms that are related to Industry 4.0, such as: Cyber-physical Systems (CPS), Internet of Things (IoT), Internet of services (IoS), intelligent manufacturing, intelligent product, Machine to machine (M2M), Big Data, and Cloud computing. On the other hand, other authors for example Blanchet, Rinn, Von Thaden and De Thieulloy (2014) add other terms to those already mentioned, such as robotization, connectivity, energy efficiency and decentralization, virtual industrialization, and Cybersecurity.

In Kagermann's group-work mention the Industry 4.0 applicability as follow (Kagermann et al., 2013):

- Customer requirements personalization or customization
- Flexibility of the processes taking dimensions such as quality, time, risk, strength, price, environmental compatibility, etc.
- Be able to make the right decisions, even in the short term to adapt to flexibility.

- Productivity and efficiency of resources.
- Potential for added value through new services, taking as a possible reference the data analysis (big data).
- Work design according to the organization.
- Work-life balance of employees at work and at home.
- Competitiveness as a space for high salaries.

In the context of Smart Manufacturing, the vision is contemplated that manufacturing processes, activities and tasks, machinery and equipment, suppliers, and products that are related through the supply chain, can be coupled into data and models as nodes in a secure network (Davis, Edgar, Porter, Bernaden & Sarli, 2012).

The topics declared in the mapping of the Smart Manufacturing Systems work environment are many. Some of them could be: Computer Aided Design (CAD): Computer Aided Engineering (CAE); Computer Aided Manufacturing (CAM); Simulation; Flexible Manufacturing System (FMS), Manufacturing Operations Management (MOM); Design for Manufacturing and Assembly (DFMA); Design for supply Chain Management (DFSCM); Continuous Process Improvement (CPI), Continuous Commissioning (CCX): Supply Chain Management (SCM); Enterprise Resource Planning (ERP); Human-Machine Interface (HMI); Operation & Maintenance (O&M); Quality Management System (QMS), among other terms (Lu et al., 2016).

As in industry 4.0, the SMLC has focused its action agenda on activities aimed by collaborative manufacturing facilitated by a Smart Manufacturing Platform with shared capacity and that seeks the following (Smart Manufacturing Leadership Coalition, 2011):

- Substantially reduce development and implementation costs of manufacturing-oriented simulation and modeling processes.
- Reduce costs for the Information Technology infrastructure.
- Access to Smart Manufacturing App and new models for innovation.
- A digital business system for intelligent manufacturing applied and that allows obtaining performance metrics of these processes.
- Implementation of test benches.
- Dynamic participation of small, medium and large companies.

As a result of the unification of the previous criteria, a graphical representation of the terms, scopes and some components related to Industry 4.0 and Smart Manufacturing is shown.

The Figure 1 shows elements that can affect the implementation of the industry 4.0, as well as the potential synergy among them, which can be included by SMEs under criteria of the cyber-physical systems.

On the other hand, the Figure 2 shows the scope and potential achievements that arise from the application of industry 4.0 by enterprises.

The figures indicate that the implantation may be addressed by the transition to a dynamic economy based on the coordination customer-enterprise that allows to individualize the customers' needs. Thus, looking for the production of individual units in very small amounts, followed by the dynamic design of the product/service that satisfies such requirements. The information generated by Big Data and Cloud Computing enables an optimal decision-making. Based on that, an interrelation of administrative and management approaches is generated, these guarantee the customer satisfaction while taking care of quality, productivity, and sustainability of the enterprise.

The summary described above, is especially important to the industrial value chains considering that all of its production models will be affected by strong social, technological, and economic transformations (Gutarra & Valente, 2018). In this sense, the SMEs will face a global scenario of great complexity and competitivity where the new business opportunities will be linked to a high capacity of using technologies. SMEs must think about considering the digital opportunities to integrate its supply chain and relate them to the customers' needs in an integral way; additionally, they could transform their production processes (SAIN4, 2016).

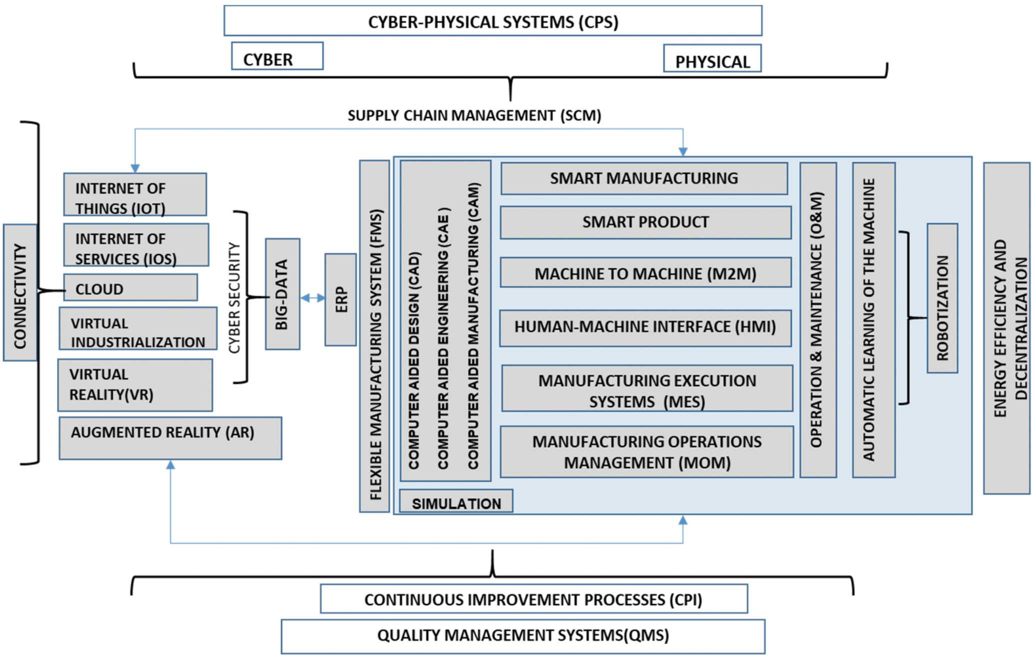

Figure 1. Synthesis of the fourth industrial revolution elements (Ávila & Gil, 2020)

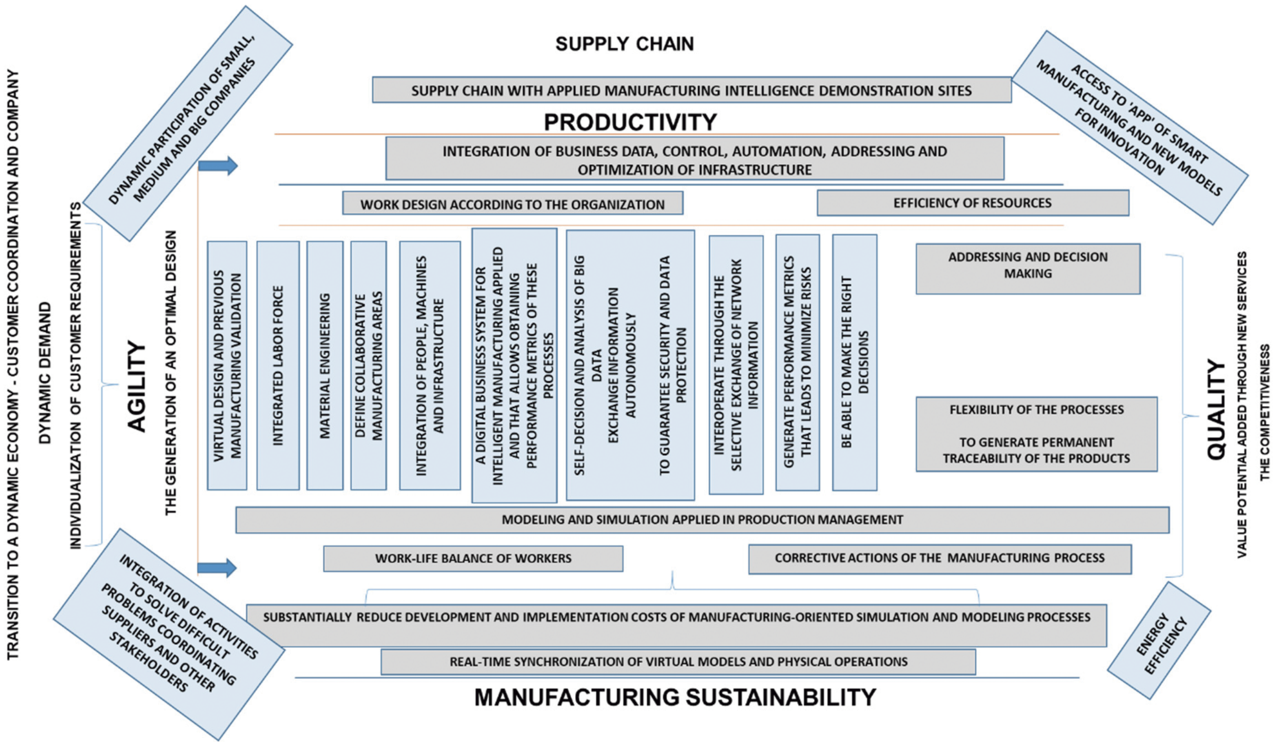

Figure 2. Synthesis of the scope of the fourth industrial revolution (Ávila & Gil, 2020)

The population of SMEs is composed by very diverse enterprises in terms of age, size, property, business models, and profiles. The heterogeneity of the company is important to cover the innovation, productivity, employment generation, and incomes, but it is equally important when the response and adaptation of the economies to the mega-tendencies such as the Industry 4.0 is thought. (OECD, 2019).

Considering the previously said, it is important that SMEs take action in the generation of strategies that allow the application of macro elements that compose the essence of Industry 4.0, such as the ones shown in the Figure 1 with the purpose of finding a successful and sustainable digital transformation of the enterprise.

2.2. Previous Maturity Models from the Literature Review

The topic Industry 4.0 in general, and the measurement of the degree of maturity is a recent topic that has been studied mainly in Europe. In the industry 4.0 field, it is important to highlight that enterprises may have two periods for the appropriation: one is preparations, and the other one, is the implementation's maturity. The preparation can be distinguished from maturity in the following way: preparation is assessed before participating in the maturity processes, meanwhile, maturity is assessed since the real implementation. In general, the term "maturity" refers to the level of real implementation in which the enterprise is ready for what it wants to measure or assess. The maturity can be assessed either quantitatively or qualitatively with criteria of discrete of continuous variables (Schumacher, Erol & Sihna, 2016).

To measure the elements and scope of Industry 4.0 in companies, several authors have generated qualitative and quantitative tools, which glimpse the possible current state of the levels of implementation of Industry 4.0 within companies, among the authors we can highlight the following works:

Wagire, Joshi, Rathore and Jain (2020) have proposed an Industry 4.0 maturity model, which is empirically grounded and technology-focussed for assessing the maturity level of Indian manufacturing organisations. The model comprises up to 7 dimensions and 38 maturity ítems.

Chonsawat and Sopadang (2019), defined the maturity model to assess the Smart SMEs readiness. In this model, the main important dimension is Manufacturing and Operations, People Capability, Technology Driven Process, Digital Support and the last important is Business and Organization Strategy.

Gökalp, Şener and Eren (2017), generated a model with the objective of providing a tool to evaluate the current maturity stage of Industry 4.0 of a manufacturer and to identify concrete measures that help it reach a higher maturity stage in order to maximize the economic benefits of Industry 4.0. The model was built based on the SPICE (Software Process Improvement and Capability determination - SPICE) model.

Dennis, Ramaswamy, Ameen and Jayaram (2017) generated a model called the Asset Performance Management Maturity Model (APM), which can help organizations understand their current capabilities and skills, and identify a sequence of steps necessary to advance to the next level.

Weber, Königsberger, Kassner and Mitschang (2017) generated the M2DDM - Maturity Model for Data Driven Manufacturing with a focus on IoT, in which they present the interaction of the value chain at different levels of the organization, in which the aims to reach a high level of maturity through an iterative process. This model does not characterize the elements used to measure the levels of maturity and implementation in companies.

Leyh, Schäffer, Bley and Forstenhäusler (2016), presented a maturity model called System Integration Maturity Model Industry 4.0 (SIMMI 4.0) that allows to a company to classify its IT systems landscape with a focus on Industry 4.0 requirements.

Ganzarain and Errasti (2016) determined the process model by stages to guide and train companies in the identification of new diversification opportunities within Industry 4.0. The systematic completion of the stages will lead a company to a specific individual evaluation and to have a collaborative vision with other companies.

Jung et al. (2016) present the Smart Manufacturing System Readiness Assessment (SMSRL) model which measures the organization's readiness to implement Industry 4.0. The approach is based on the concept of smart manufacturing in which the important thing is the ability to use information effectively.

Schumacher et al. (2016), developed a model that allows companies to evaluate their maturity in relation to Industry 4.0 and reflect based on this evaluation, on the adequacy of their current strategies. The important matter about this model is that the authors sought to transform the concepts that they considered abstract in intelligent manufacturing issues into elements that could be measured in real production environments.

When reviewing each of the models presented by the previous authors, it is generally evident that general dimensions are taken into account focused on measuring the level of application of Industry 4.0. The measurement scales, for the most part, are given on a Likert scale. The validation of these models is characterized by being applied to a specific company.

3. Research Design

To design and apply the model to assess the level of maturity of industry 4.0 in manufacturing SME, it was established a path to carry out the research. Figure 3 specifies the methodology followed to define the model of maturity to be applied and the details of stages expected to be achieved until applying an assessment instrument to a significant sample of SMEs.

3.1. Results

From the stages of the research design, the results obtained in each of them are presented below.

3.2. Development of the Model

For designing the model, it is relevant to determine -considering the elements and scope of industry 4.0- the independent and dependent variables, the possible assessment models of maturity levels that have been applied in the world and the generation of the dimensions to be later used when assessing the maturity level of the SMEs.

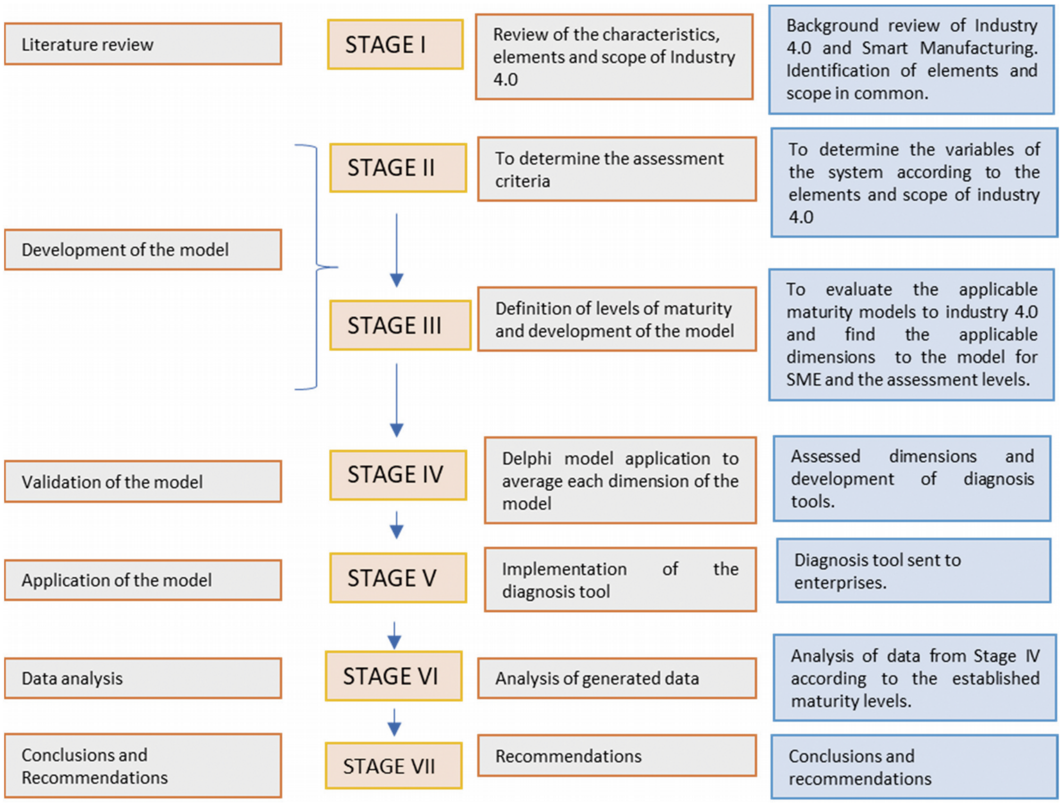

Figure 3. Research pathway

3.2.1. Definition of the Variables

Next, the approaches that have been considered in the maturity assessment of the SMEs are established. Likewise, from what was presented in Figure 1 and Figure 2, it is presented the relationship amongst the elements, scope, and dimensions with the aim of determining the assessment model for SMEs.

Within the scenario proposed by Industry 4.0, in Figure 4 the determined variables of the model are presented.

- Independent variable: application of industry 4.0 tools and Smart manufacturing in the SMEs in the city of Bogotá-Colombia.
- Dependent variable: Level of industrial automation in the SMEs of the city of Bogotá-Colombia.

Figure 4 allows to observe the independent existence of cyber and physical elements, nevertheless, these can be dependent one on another, which can generate an application context of established tools from industry 4.0 and smart manufacturing application. These gathered elements, both cyber and physical directly affect the processes' optimization and the sustainability of the manufacture, and as a consequence, the organization.

On the other hand, these cyber and physical elements can point to one or several of the scopes on which industry 4.0 empowers. The Figure 5 presents the interconnection between the elements' group and the scope of industry 4.0. Hence, these elements are oriented to optimize the processes, to make flexible the manufacturing systems, to maintain the quality of the feedstock – resources, ongoing and finished products- and, lastly, to keep a level of productivity that along with the service would generate profitability and the sustainability of the company. All of that can be achieved by gathering and analyzing data and making decisions based on the relevant information of the processes.

A relevant topic that should be considered in the models is the difference between steps and dimensions. The dimensions are the number of areas within an enterprise that the model is assessing. The steps or scales are the number of levels or stages that the company needs to go through until a full implementation of Industry 4.0. (Amaral, Diodo & Peças, 2019). These dimensional attributes are important to assess the business maturity levels for Industry 4.0. (Basl, 2018). Table 1 shows the dimensions applied and the assessment scales of some maturity models around industry 4.0.

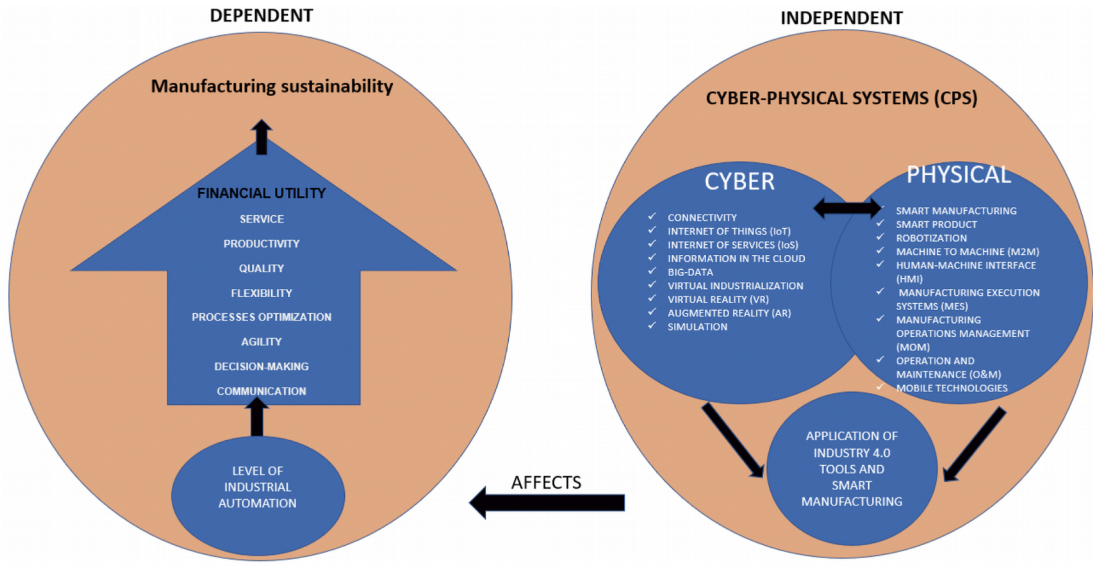

Figure 4. Relationship between independent and dependent variables

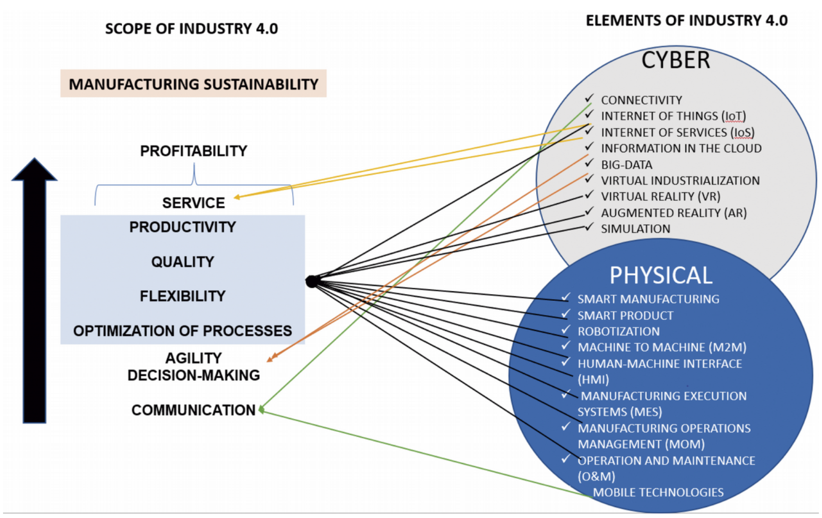

Figure 5. Relationship between elements and scope of Industry 4.0

Making a review of the models described in Table 1. it is observed that aspects such as strategic, managerial, technical, and human intervention points of view permeate. Oztemel and Gursev (2020) mention that the integration of the elements of Industry 4.0 is done horizontally (through all participants in the entire value chain) and vertically (in all automation levels) of a given company as a whole. The dimensions shown in Table 1 contextualize vertical integration which aspects of the Organization, personnel, machines, processes, and products are taken. Likewise, they connote horizontal integration in topics such as customer service, suppliers, among others.

Authors	Name of model	Dimension in model	Evaluation scale	Does the model allow A direct evaluation?	Take into account SMEs?
Wagire et al. (2020)	Development of maturity model for assessing the implementation of Industry 4.0: learning from theory and practice	1-People and culture 2-Industry 4.0 awareness 3-Organisational strategy 4-Value chain and processes 5-Smart manufacturing technology 6-Product and services oriented technology 7-Industry 4.0 base technology	Level 1: Outsider Level 2: Digital Novice Level 3: Experienced Level 4: Expert	Characterized its implementation in companies	NO
Chonsawat and Sopadang (2019)	The Development of the Maturity Model to evaluate the Smart SMEs 4.0 Readiness	1- Business and Organization Strategy 2- Manufacturing and Operations 3- Technology driven Process 4- Digital Support 5- People Capability	0-Is irrelevant 1-Is relevant but not implemented 2-Implemented in some area of the organization. 3-Implemented in the most area of the organization. 4-Full implementation.	It does not characterize its implementation in companies	YES
Gökalp et al. (2017)	Software Process Improvement and Capability determination (SPICE)	1- Asset Management 2-Data governance 3-Application management 4-Process transformation 5-Organizational alignment	1-Incomplete 2-Performed 3-Managed 4-Established 5-Predictable 6-Optimizing	It does not characterize its implementation in companies	NO
Dennis et al. (2017)	APM - Asset Performance Management Maturity Model	1-Asset information management. 2-Process management. 3-Reliability and performance. 4- Governance and standards. 5-People and culture management. 6-Tools and technologies.	0-Ad hoc/initial 1-Defined/preliminary adoption 2-Compliant/normative 3-Evolving/integrated enterprise 4-Execution 5-excellence	It does not characterize its implementation in companies	NO
Weber et al. (2017)	M2DDM - Maturity Model for Data Driven Manufacturing	1-Data storage and compute 2-Service- oriented architecture 3-Information integration 4- Digital twins 5-Advanced analytics 6-Real-time capabilities	0-Nonexistent IT integration 1-Data and system integration 2- Integration of Cross-life- cycle data 3-Service orientation 4-Digital twins 5-Self-optimising factory	It does not characterize its implementation in companies	NO

Authors	Name of model	Dimension in model	Evaluation scale	Does the model allow A direct evaluation?	Take into account SMEs?
Schumacher et al. (2016)	Maturity Model for Assessing Industry 4.0 Readiness and Maturity of Manufacturing Enterprises	1-Strategy 2-Leadership 3-Customers 4-Products 5-Operations 6-Culture 7-People 8-Governance, 9-Technology	1- level 1 describes a complete lack of attributes 2-level 5 represents the state-of-the-art of required attributes.	It does not characterize its implementation in companies	YES
Jung et al. (2016)	Smart Manufacturing System Readiness Assessment (SMSRA)	1-Organizational maturity 2-Information technology maturity 3-Performance management maturity. 4-Information connectivity maturity	0-Not performed 1-Initial 3-Managed 5-Defined 7-Qualitative 9-Optimizing	It does not characterize its implementation in companies	NO
Ganzarain, and Errasti (2016)	Three stage maturity model in SME's toward industry 4.0	1-Envision 4.0 Vision 2-Enable Roadmap 3- Enact Projects	1-Initial 2-Managed 3-Defined 4-Transform 5- Detailed Business Model	It does not characterize its implementation in companies	YES
Leyh et al. (2016)	SIMMI 4.0 - System Integration Maturity Model Industry 4.0	1-Vertical integration 2-Horizontal integration 3-Digital product development 4-Cross- sectional technology criteria	1-Basic digitalization level 2-Cross- departmental digitalization 3-Horizontal and vertical digitalization 4-Full digitalization 5-Optimized full digitalization	It does not characterize its implementation in companies	YES
Lichtblau, Stich, Bertenrath, Blum, Bleider, Millack, et al. (2015)	IMPULS - Industry 4.0 Readiness	1-Strategy and organization 2-Smart factory 3-Smart operations 4-Smart products 5-Data driven services 6-Employee	0-Outsider 1-Beginner 2- Intermediate 3-Experienced 4-Expert 5- Top performer	It does not characterize its implementation in companies	NO

Table 1. Summary of dimensions and assessment scale for maturity models in Industry 4.0

3.2.2. Determination of the Model's Dimensions

Considering the validation of some maturity models shown in the Table 1, and aligned with the purpose of this article, the model that has been used as reference is the one proposed by Schumacher et al. (2016). Such model optimizes the dimensions with a technological approach, including organizational elements. The nine (9) dimensions covered by these authors are focused on sixty-two (62) maturity elements. The path of evolution of each dimension experiences five levels of maturity, where the level 1 describes a total lack of attributes that support the concepts of Industry 4.0 and the level 5 represents the state of the art of the required attributes.

For this paper, it is undoubtedly necessary to describe these dimensions that could be used to determine the maturity of industry 4.0; it is because of that, the elements and scope of industry 4.0 should be well-thought-out according to the presented model by Schumacher et al. (2016).

In this sense, Figure 6 shows the possible dimensions that may be used as a model to be applied to SMEs.

Figure 6 highlights 8 dimensions in which the Culture and Employees dimension gathers the others, because the implementation of industry 4.0 elements depends on the organizational culture and the people empowerment in each one of their areas.

3.2.3. General Description of the Dimensions

Next from Table 2 to Table 9, the dimensions that belongs to the model are listed and described, as well as the questions that work as criteria to assess the maturity level.

3.2.3.1. Service

Customers' data utilization, response to petitions, claims, and complaints through different digital media, interaction customer/Enterprise (sales/services/designs/process). The summary in Table 2.

Dimension	Concept	Index
Service	Systems of attention to customer's requirements (before-during-after).	What is the level of combination between physical products in the portfolio of the company towards the customer?
		To what extent does the enterprise use different channels to interact with a customer?
		Level of interactions with customers' monitoring performed by the company
		Level of response to customers' needs by the company.

Table 2. Dimension related to service

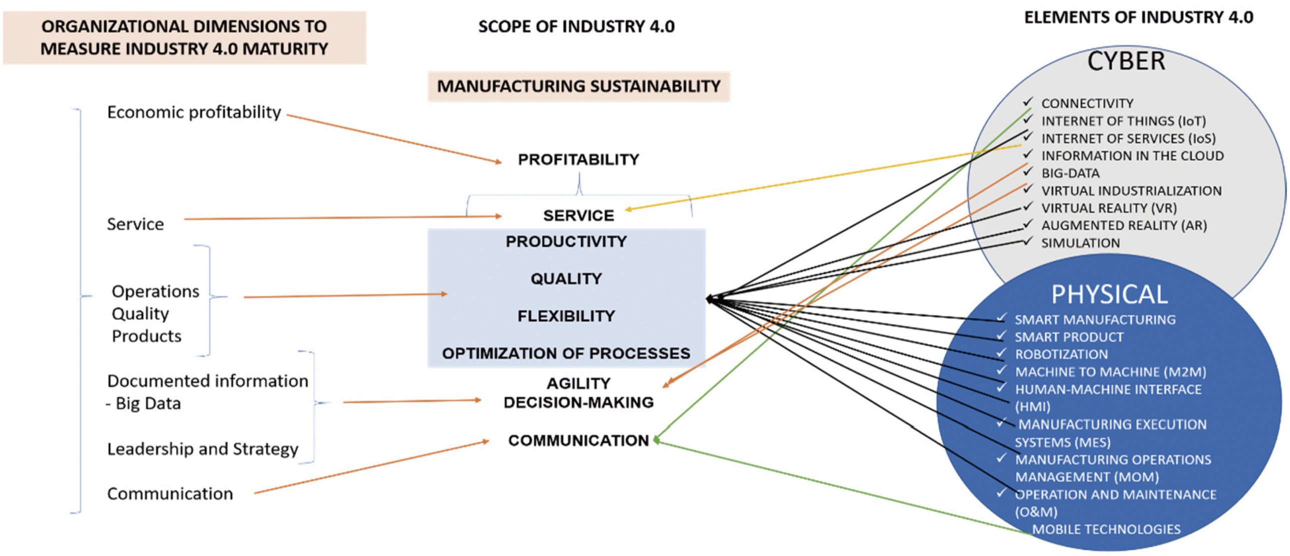

Figure 6. Relationship among the dimensions of maturity of industry 4.0 and the scope and achievements that arise from its application

3.2.3.2. Operations

Decentralization of processes, modelling, and simulation, application of CAD, CAE, CAM, virtual and augmented reality, human-machine interfaces, robotization, utilization of machine-to-machine communication.

Individualization of products, digitalization of products, integration of products in other systems, interconnected product, and service. See Table 3.

Dimension	Concept	Index
Operations	Use of processes, procedures and technologies that enhance productivity.	To what extent are key processes of the company automated?
		To what extent are data generated by information systems shared and utilized between the areas?
		To what extent are the enterprises' processes operationally integrated?
		Number of machines that have technology for remote supervisory control and data acquisition.
		Planning level and processes sequencing based on ERP.
		Level of use of simulation in processes.
		To what extent does the company have digital tools that promote flexibility and enhance efficiency in productive processes?
		Level of telecommuting that the company developed before the pandemic.
		Level of telecommuting that the company develops (after the pandemic).
		What is the adaptability capacity of the company to manage shorter batches of production and for different products?
		Level of implementation of methodologies/philosophies with an approach to processes.

Table 3. Dimension related to operations

3.2.3.3. Quality

Safety protocols related to complying the quality parameters, devices for detecting errors in the process and in the product. See in Table 4.

Dimension	Concept	Index
Quality	Drastic minimization of nonconformities.	What is the level automation of the products' quality control?
		To what extent does the company use statistical control of the processes?
		Level of capabilities with an approach to quality control of the staff in charge.
		Level of implementation of continual improvement processes.
		Number of international certifications for product and process. (ISO, BASC, NORSOCK, PRODUCT, PROCESS).
		Level of implementation of methodologies with an approach to quality management.

Table 4. Dimension related to the quality of the products

3.2.3.4. Product

Application of cyber-physical systems for the design, production, and control of products. See Table 5.

Dimension	Concept	Index
Products	Inclusion of cyber-physical systems to the design of the products.	Level of innovation of products and/or services, or their significant yearly improvements.
		Level of use of CAD-CAE and CAM for the design and simulation of products (design, engineering and manufacturing – computer assisted).
		To what extent does the company have the ability to configure families of products and services throughout time?
		Level of flexibility in products to quickly satisfy customers' needs.

Table 5. Dimension related to the product

3.2.3.5. Documented Information - Big Data

Skills and methods of management, existence in central coordination for I4.0, data analysis for improvement and innovation. Approach to technologies and procedures to collect data (structured and unstructured) generated in operative processes of the enterprise, which are managed by the company or external institutions for its latter processing and comprehension in the decision-making. Assessment of devices that are connected to internet and that allow providing information. See Table 6.

Dimension	Concept	Index
Documented - Information - Big Data	Use of data collection, storage, management and processing systems, both structured and unstructured and generated in the operative processes of the enterprise, used in the decision-making.	To what extent do products, processes and services of the company allow data/information collecting (before, during and after)?
		Level of Access to data bases from any point of the company.
		Level of implementation of available information platforms on the cloud.
		Operational and technological capacity to process data.
		To what extent are cyber-safety and protection of information tools implemented in the enterprise?
		Level of training of the cyber-safety staff in the company.
		Level of use of control panels of the information. (BSC, Dash Board…)
		Number of physical devices for storing and communicating the information.

Table 6. Dimension related to the management of documented information – Big Data

3.2.3.6. Leadership and Strategy

A first key element or dimension is leadership, as mentioned by ISO 9001:2015 (International Organization for Standardization, 2015) it's having a serious commitment and continuous satisfaction of the customer from the organizations' managers. It's fundamental to determine the actions and objectives to be developed for implementing the elements of industry 4.0 See Table 7.

Leadership is accompanied by a good strategy that allows to verify actions of formulation and application of strategies routed to implement the elements of industry 4.0 that create differential value (World Economic Forum, 2016). Within the strategy, the implementation of the roadmap I4.0, available resources for the development, adaptation of business models under I4.0 criteria, and protection of intellectual property would be found (Schumacher et al., 2016).

Dimension	Concept	Index
Leadership and Strategy	Organizational alignment for adopting I4.0 Availability of strategic and financial planning oriented to implementation of I4.0.	Level of use of a route plan for the planification of activities of industry 4.0 in the company.
		To what extent does the organization support the collaboration among stakeholders such as providers, customers, universities, research centers, etc., to seek for solutions in I4.0?
		What is the level to which the company has identified, valued and prioritized innovative proposals of industry 4.0?
		Level to which -during the last two years- the structure, functions and scope of the organization has changed to improve its flexibility, efficiency and effectiveness allowing a better work of internal teams and collaborative spaces.
		To what extent is digitalization a handled aspect within the company?
		To what extent does the organization use data analysis (Bid Data) to make strategical decisions?
		What is the level of implementation of transformation solutions to I4.0 in the company?
		Level to which the senior managers of the enterprise have a vision of the digital future of the business.
		Level of existence of roles and responsibilities for leading digital proposals in the company.

Table 7. Dimension related to leadership and strategy

3.2.3.7. Communications

Validation of the significant changes in the ways in which the enterprise handles the communications both within the companies and towards the stakeholders. See Table 8.

Dimension	Concept	Index
Communication	Mechanisms of communication in the internal and external contexts of the enterprise.	To what extent does the company use networks (digital, social, scientific, technological, etc.) for having access to better content, quality of information and positioning opportunities?
		What is the level to which the enterprise makes use of internet to communicate to its staff internal information of the company?
		To what extent do the departments of the company share information through the cloud or other digital mechanisms

Table 8. Dimension related to communication

3.2.3.8. Culture and Staff

The organizational culture as a central aspect in the digital transformation. Here, it is expected to visualize the characteristics of the entrepreneurs' places of work open to its surroundings and highly creative, where it is constantly promoted the experimentation with new technologies. Knowledge interchange, open innovation, and collaboration between companies, value of ICTs in the enterprise. Likewise, the degree of competencies and skills in the staff about I4.0 is verified. The details in Table 9.

Dimension	Concept	Index
Culture and Staff	Knowledge interchange, open innovation and collaboration between areas Competencies and skills in the staff about new technologies Willingness of the staff for analyzing continuously, and if necessary, to adapt their own behavior towards Industry 4.0 topics.	What level of interiorization of I4.0 principles is embedded in staff culture of the company?
		To what extent are actions that seek for a culture of innovation with approach to technological transformation promoted inside the company?
		Level of participation in open innovation and collaboration between areas.
		Does the enterprise have staff trained in industry 4.0 with knowledge and use of ICTs (internet of things, computer, telephone, applications, search of information, among others)?

Table 9. Dimension related to culture and staff

In order to carry out the assessment of the previous dimensions, five different criteria have been established using a Likert scale; within them, the analysis performed for each element of industry 4.0 is considered, as well as the verification of the level achieved by the company during the implementation of the expected elements. Each dimension built in this paper, covers both elements and scope. The levels of maturity are described next:

- Level 1: it represents the level to which the surveyed companies have not yet concretely generated any activity or application of elements of industry 4.0
- Level 2: it represents the level to which the surveyed companies have started strategically activities of research and analytical studies, as well as pilots to include and appropriate technology.
- Level 3: it represents the level to which the surveyed companies have partially applied technologies to their processes.
- Level 4: it represents the level to which the surveyed companies have highly applied technologies to their processes.

- Level 5: it represents the surveyed companies that have implemented different elements and have achieved the scope that is covered by the industry 4.0.

As an example of the previously said, the Figure 7 shows the question #2 of the Dimension of Communication.

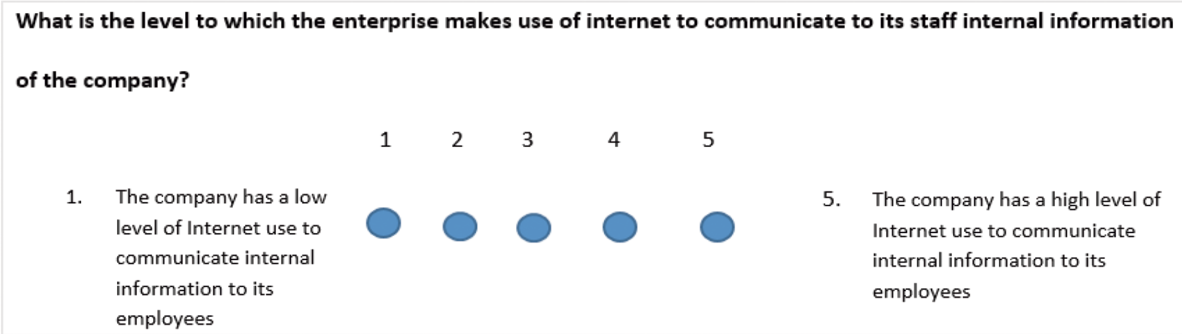

Figure 7. Characterization of the questions or indexes of levels of maturity of industry 4.0 dimensions

For information gathering, a structured survey has been built from the dimensions of Industry 4.0. The survey is framed into a questionnaire that will be sent to a randomly taken sample of SMEs of the Bogotá city. The questionnaire is based on questions (index of maturity) targeting managers, specialists around manufacturing or technology of the enterprises. The questions are of ordinal-qualitative character.

3.3. Formalizing the Suggested Maturity Model for SMEs

The model applied by Schumacher et al. (2016) and the possible dimensions have until now served to measure the level of maturity of industry 4.0 in an enterprise. However, the proposed model will work as a model to do the same in several enterprises of the same sector.

In this sense, the formulas that highlight the model would be correspondingly in the following way: The Formula 1, expresses the level of maturity by dimension D of I4.0 for an enterprise, and the Formula 2 expresses the level of maturity by dimension D for all the enterprises of the case study.

Formula 1: $M_{Di} = \frac{\sum_{i=1}^{n} M_{Di} * g_{Di}}{G_{Di}}$ Maturity by dimension of industry 4.0 for an enterprise.

Formula 2: $M_{Dj} = \frac{\sum_{j=1}^{NE} M_{Dj}}{NE}$ Maturity of enterprises of the same sector in regards of each Dimension of industry 4.0.

Where:

"M" corresponds to the Maturity Level.

"D" corresponds to the Dimension to be assessed in the enterprise.

"i" corresponds to the index of maturity i of the Dimension "i". (Index of maturity "i" = the question "i").

"G" corresponds to the averaging factor for the Dimension "i" (found using the Delphi method).

"g" corresponds to the averaging factor by index or maturity "i", where g_{Di} = (G_{Di} / summatory of the number of indexes of maturity of Dimension "i")

"n" corresponds to the number of indexes of maturity of each Dimension "i".

"j" corresponds to the enterprise "j" that has been assessed with the indexes of maturity of the Dimensions "i".

"NE" corresponds to the number of enterprises that were assessed with the indexes of maturity of the respective Dimensions "i".

3.4. The Proposed Model Validation

The whole model validation has been structured in two-fold. The first one, a staff of expert committee have been consulted (Delphi method) to check the suggested attributes of each dimension. The other one, applying the questionnaire to an intentional sample of SME

3.4.1. Applying the Delphi Method to Average Each Dimension of the Model

In order average each dimension, it was carried out a Delphi method with businesspeople that know about Industry 4.0, teachers and enterprises executives. In this exercise the following people participated: 2 experts, 3 managers, 2 teachers of the ICT area and 4 middle-management officers.

In Table 10 shows the result of the assessments, where it is used a scale from 1 to 5 according to the level of importance that each participant assigned to the Dimension for achieving the implementation of elements of industry 4.0 and its scope.

Dimensions	Experts		Business people (senior managers)			Teachers		Middle-manager				Average by dimension (G_{Di})	# of indexes of maturity by dimension	Average by index of maturity of each dimension (g_{Di}) (G_{Di})/ summatory of the number of indexes of maturity of Dimension "i")
	1	2	3	4	5	6	7	8	9	10	11			
Leadership and Strategy	4.5	4	4.5	5	4.5	4	3.8	4.5	5	5	4.5	**4.48**	**9**	**0.498**
Communication	4	4.5	4	4.2	4	4.5	4	4.5	4	4.3	4.5	**4.23**	**3**	**1.409**
Culture and Staff	5	4.5	4.5	4	4.3	4.2	4.5	4.3	4.5	4.5	4.3	**4.42**	**4**	**1.105**
Documented-Information (Big Data)	5	5	4.5	4.5	4.8	4.5	4.7	4.3	4.4	4	4.8	**4.59**	**8**	**0.574**
Operations	5	4.5	4	4	4.5	4.5	4.5	5	5	5	5	**4.64**	**11**	**0.421**
Product	5	5	5	5	5	5	5	5	5	4.8	4.5	**4.94**	**4**	**1.234**
Quality	4.5	4.7	5	4.7	4.5	4.5	4.5	4.5	4.3	4.7	4.7	**4.60**	**6**	**0.767**
Service	5	5	5	4.7	5	5	5	5	4.8	4.5	5	**4.91**	**4**	**1.227**

Note: To clarify, the average "g_{Di}" which has a formula g_{Di} = (G_{Di} / summatory of the number of indexes of maturity of Dimension "i", was taken due to the fact that each index of maturity has the same weight on the corresponding Dimension "i".

Table 10. Average of the dimensions

3.4.2. Validation the Model by a Pilot Testing

For the validation of the method, the sample of enterprises was determined by means of the intentional sampling method, this is because what is initially intended is to approve the model that has been developed. Thus, 23 enterprises are taken as reference; out of this chosen companies, the 63.6% corresponds to the classification of medium-sized enterprises and 36.4% to small enterprises.

Regarding to simplify the model application understanding, it is presented as an explanation the analysis for one relevant dimension of it. With this in mind, Dimension 2 (Communication) have been used and the score for the 3 indexes of maturity or questions in this dimension are presented in Table 11, according to the data gathering from the SME of the sample.

	Index of maturity 1	Index of maturity 2	Index of maturity 3
Enterprise 1	4	5	3
Enterprise 2	5	5	5
Enterprise 3	4	5	5
Enterprise 4	5	5	4
Enterprise 5	5	5	5
Enterprise 6	5	5	5
Enterprise 7	5	5	5
Enterprise 8	5	5	5
Enterprise 9	4	5	4
Enterprise 10	5	4	4
Enterprise 11	4	4	4
Enterprise 12	5	5	5
Enterprise 13	5	5	5
Enterprise 14	5	5	5
Enterprise 15	5	4	5
Enterprise 16	4	4	4
Enterprise 17	5	4	5
Enterprise 18	4	4	4
Enterprise 19	4	4	4
Enterprise 20	5	5	5
Enterprise 21	5	5	5
Enterprise 22	3	3	3
Enterprise 23	1	4	5

Table 11. Scores given by the enterprises to MD2 = "Communication"

For the dimension "**Communication"** the average factor according to Table 10 by dimension is G_{Di}= 4,23, and the average factor by index of maturity for each dimension is g_{Di} = 1,409. To do so, the values in Table 11 are multiplied by the average factor.

In attempt to determine MD2 of "Communication", the following calculation is made:

Take the values of each enterprise, in this case, Enterprise 1, as shown in Table 12.

	Index of maturity 1	Index of maturity 2	Index of maturity 3
Enterprise 1	4	5	3

Table 12. Scores given by Enterprise 1

a) The value given by the enterprise is multiplied by the average factor by index of maturity of each dimension g_{Di} = 1,409. The value of maturity of the dimension "Communication" for Enterprise 1 is obtained from adding all the indexes of maturity and dividing the average factor by dimension G_{Di} = 4,23. In Table 13 the result for Enterprise 1 is shown.

	Index of maturity 1	Index of maturity 2	Index of maturity 3	M_{D2}
Enterprise 1	4*1.409= 5.6	5*1.409=7.0	3*1.409=4.2	=(5.6+7.0+4.2)/ 4.23=4.0

Table 13. Level of maturity of the Dimension "Communication" for Enterprise 1

b) The general value of the dimension "Communication" ,or all the companies is gotten from averaging M_{D2}, for obtaining a final score for the dimension of 4,51, as presented in Table 14; meaning that the Level of Maturity M_{D2} for these enterprises of the sample is between Levels 4 and 5, demonstrating that is in a stage of ***"high level of application of technologies to its communication processes".***

	Index of maturity 1	Index of maturity 2	Index of maturity 3	M_{D2}
Enterprise 1	5.6	7.0	4.2	4.0
Enterprise 2	7.0	7.0	7.0	5.0
Enterprise 3	5.6	7.0	7.0	4.7
Enterprise 4	7.0	7.0	5.6	4.7
Enterprise 5	7.0	7.0	7.0	5.0
Enterprise 6	7.0	7.0	7.0	5.0
Enterprise 7	7.0	7.0	7.0	5.0
Enterprise 8	7.0	7.0	7.0	5.0
Enterprise 9	5.6	7.0	5.6	4.3
Enterprise 10	7.0	5.6	5.6	4.3
Enterprise 11	5.6	5.6	5.6	4.0
Enterprise 12	7.0	7.0	7.0	5.0
Enterprise 13	7.0	7.0	7.0	5.0
Enterprise 14	7.0	7.0	7.0	5.0
Enterprise 15	7.0	5.6	7.0	4.7
Enterprise 16	5.6	5.6	5.6	4.0
Enterprise 17	7.0	5.6	7.0	4.7
Enterprise 18	5.6	5.6	5.6	4.0
Enterprise 19	5.6	5.6	5.6	4.0
Enterprise 20	7.0	7.0	7.0	5.0
Enterprise 21	7.0	7.0	7.0	5.0
Enterprise 22	4.2	4.2	4.2	3.0
Enterprise 23	1.4	5.6	7.0	3.3
			M_{Dj}. j=23	4.51

Table 14. Level of maturity of the Dimension "Communication" for all enterprises

3.5. Data Analysis

In Figure 8 it can be observed the score of the different dimensions related to industry 4.0 in the companies used as sample to apply the model.

The dimension of communication is remarkable since the enterprises have internet service in all the areas, they have a high degree of communication using internet with the stakeholders and workers. Companies also highly use networks to have better access to better content, quality of information and positioning opportunities. Finally, the areas of the enterprises share -to a great extent- information throughout cloud alternatives or other digital alternatives.

On the contrary, it can be observed that the enterprises in the Culture and Staff, Leadership and strategy and Operations dimensions, are placed within a Level of Maturity bordering Level 3. It can be said then that these companies "have partially applied technologies to their processes".

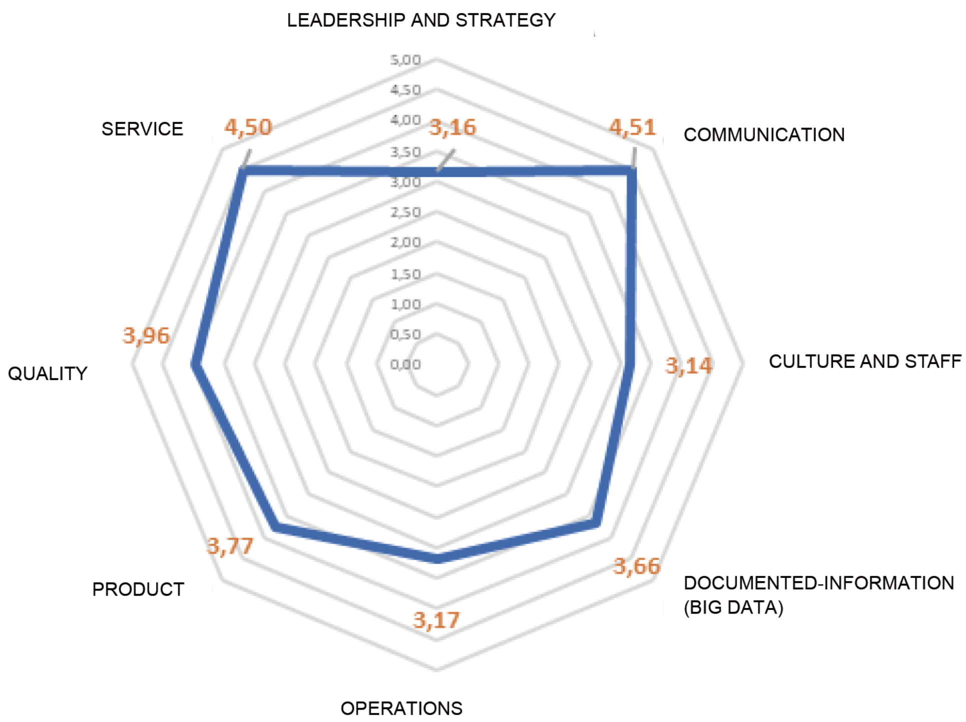

Figure 8. Level of maturity for the 23 surveyed enterprises

4. Results Discussion

Categorizing Industry 4.0 is framed by different authors, particularly of German origin. The main component, the cyber-physical, is understood by the authors from different perspectives and connotations.

Inside the context to assess the levels of maturity of Industry 4.0, it can be appreciated that some authors have different approaches for assessing the level of maturity; they present very different dimensions and assessment criteria, giving limitations in their scopes. (As shown in Table 1)

The design of the Model of Maturity to apply to SMEs in Colombia has been Developed considering the global approaches, taking care of the own criteria of the national enterprises. It is because of that, that the average of the dimensions that are assessed in the companies have been assessed with different actors that have an understanding on industry 4.0 criteria. In this sense, the choosing the candidate SMEs to apply the Maturity model to was not an easy task due to not having an established government or private study with rigorous criteria to determine the state of SMEs.

This paper showed that the implementation of the Industry 4.0 elements is a very complex process; due to COVID-19 related issues, the enterprises have increased the use of technologies of communication and telecommuting. Then, the possible presented models by the authors before 2020 (during pandemic stage) should be evaluated according to the new demands of the markets and companies.

5. Conclusions and Recommendations

A sematic representation about the concepts and terms of Industry 4.0 have been reached to understand previously the relevance of them to be later applied in any suggested maturity model (Figures 4 and Figure 5).

To broaden their knowledge of the related dimensions and assessment attributes included in some of the reviewed current maturity models, about those elements was summarized in the Table 1. In fact, an important enforce of alignment between the dimensions considered and the corresponding maturity level of this enterprise/firm will be obtained from each one of this models.

Once that recent maturity models were reviewed an analyzed, taking into account our research premises (to apply in some local Colombian SMEs for a specific sector), it was selected as referential resource the Schumacher et al (2016) model because it emphasize into the SME profile. This cited model have been updated with some of our relevant dimensions and improved whit the specific terms (highlighted in Figure 6).

The application of this updated model for some SME in Bogota City help us to understand and consider some specific dimensions and evaluation criteria to classify the cluster of those SMEs about a specific sector under a profiles of their considered dimensions (Figure 8).

5.1. Research Contributions

The maturity model describes in detail the variables, dimensions and how to apply the measurement tool. In this sense, it allows SMEs to make an analysis of their internal context against the proposed dimensions.

In the future it will be implemented the model for the SMEs of the manufacturing sector of Bogotá, and eventually establish the current state of implementation of elements of industry 4.0. Therefore, it is expected to have the possibility of applying the model to the SMEs to other diverse economic activities.

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References

Amaral, A., Diodo, J., & Peças, P. (2019). Small Medium Enterprises and Industry 4.0: Current Models' Ineptitude and the proposal of a methodology to successfully implement industry 4.0 in small medium enterprises. *Procedia Manufacturing,* 41, 1103-1110. https://doi.org/10.1016/j.promfg.2019.10.039

Ávila, J., & Gil, R.J. (2020). Industry 4.0 and smart manufacturing convergence: profiling guidelines for a fourth revolution. *International Journal of Engineering & Technology,* 9(2), 464-473. https://doi.org/10.14419/ijet.v9i2.30476

Basl, J. (2018). Analysis of Industry 4.0 Readiness Indexes and Maturity Models and Proposal of the Dimension for Enterprise Information Systems. In: Tjoa, A., Raffai, M., Doucek, P., & Novak, N. (Eds.), *Research and Practical Issues of Enterprise Information Systems.* CONFENIS 2018. Lecture Notes in Business Information Processing, 327. Springer, Cham. https://doi.org/10.1007/978-3-319-99040-8_5

Blanchet, M., Rinn, T., Von Thaden, G., & Thieulloy, G. (2014). *Industry 4.0: The new industrial revolution How Europe will succeed.* München: Roland Berger Strategy Consultants GmbH.

Chonsawat, N., & Sopadang, A. (2019). The development of the maturity model to evaluate the smart SMEs 4.0 readiness. In *Proceedings of the international conference on industrial engineering and operations management* (354-363). Available at: http://ieomsociety.org/ieom2019/papers/97.pdf

Davis J., Edgar, T., Porter, J., Bernaden, J., & Sarli, M. (2012). Smart manufacturing, manufacturing intelligence and demand-dynamic performance. *Computers & Chemical Engineering,* 47, 145-156. https://doi.org/10.1016/j.compchemeng.2012.06.037

Dennis, M., Ramaswamy, C., Ameen, M.N., & Jayaram, V. (2017). Asset Performance Management Maturity Model, BCG Perspective, Capgemini. Available at: https://www.capgemini.com/wp-content/uploads/2017/08/asset_performance_management_maturity_model_paper_web_version.pdf

Elkaseer, A., Ali, H., Scholz, S., & Salama, M. (2018). Approaches to a Practical Implementation of Industry 4.0. *International Conference on Advances in Computer-Human Interactions (ACHI)* (141-146). Available at: https://www.researchgate.net/profile/Ahmed-Elkaseer/publication/324040762_Approaches_to_a_Practical_Implementation_of_Industry_40/links/5abfc440a6fdcccda65c38fb/Approaches-to-a-Practical-Implementation-of-Industry-40.pdf

Flores, A., Li, Y., Chen, W., Zhan, Z., Zhang, J., & Chen, L. (2015). Industry 4.0 with Cyber-Physical Integration: A Design and Manufacture Perspective. *21st International Conference on Automation & Computing*. Glasgow. https://doi.org/10.13140/RG.2.1.2502.8569

Ganzarain, J., & Errasti, N. (2016). Three stage maturity model in SME's toward industry 4.0. *Journal of Industrial Engineering and Management,* 9, 1119-1128. https://doi.org/10.3926/jiem.2073

Gökalp E., Şener, U, & Eren, P.E. (2017). Development of an Assessment Model for Industry 4.0: Industry 4.0-MM. In Mas, A., Mesquida, A., O'Connor, R., Rout T., & Dorling A. (Eds.), *Software Process Improvement and Capability Determination. SPICE. Communications in Computer and Information Science* (770). Springer, Cham. https://doi.org/10.1007/978-3-319-67383-7_10

Gutarra, R., & Valente, A. (2018). The peruvian technological MSMEs to 2030. Strategies for their insertion to industrie 4.0. *Nova Scientia,* 10(20), 754-778. https://doi.org/10.21640/ns.v10i20.1329

Hermann M., Pentek, T., & Otto, B. (2016). Design principles for Industrie 4.0 scenarios. *Hawaii International Conference on System Sciences (HICSS)* (3928-3937). https://doi.org/10.1109/HICSS.2016.488

International Organization for Standardization (2015). *Quality Management Systems - Requirements (ISO standard no. 9001:2015).* Available at: https://www.iso.org/obp/ui/#iso:std:iso:9001:ed-5:v1:en

Jung, K., Kulvatunyou, B., Choi, S., & Brundage, M.P. (2016). An Overview of a Smart Manufacturing System Readiness Assessment. *IFIP International Conference on Advances in Production Management Systems* (705- 712). Springer, Cham, Switzerland. Available at: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5921078/

Kagermann, H., Helbig, J., Hellinger, A., & Wahlster, W. (2013). *Umsetzungsempfehlungen für das Zukunftsprojekt Industrie 4.0: Deutschlands Zukunft als Produktionsstandort sichern; Abschlussbericht des Arbeitskreises Industrie 4.0.* Forschungsunion and Geschäftsstelle der Plattform Industrie 4.0. Berlin, Frankfurt/Main. Available at: https://www.acatech.de/wp-content/uploads/2018/03/Abschlussbericht_Industrie4.0_barrierefrei.pdf

Kainer, L. (2017). *Industry 4.0 – The Evolution of Business Models.* University of Nottingham.

Leyh, C., Schaffer, T., Bley, K., & Forstenhausler, S. (2016). SIMMI 4.0 – A Maturity Model for Classifying the Enteerprise-wide IT and Software Landscape Focusing on Industry 4.0. Proceedings of the *Federated Conference on Computer Science and Information Systems* (1297-1302), IEEE. https://doi.org/10.15439/2016F478

Lichtblau, K., Stich, V., Bertenrath, R., Blum, M. Bleider, M., Millack, A. et al. (2015). *IMPULS-Industrie 4.0-Readiness*. Impuls-Stiftung des VDMA, Aachen-Köln. Available at: http://www.impuls-stiftung.de/documents/3581372/4875823/Industrie+4.0+Readiness+IMPULS+Studie+Oktober+2015_eng.pdf/

Lu, Y., Morris, K.C., & Frechette, S. (2016). *Current Standards Landscape for Smart Manufacturing Systems.* NISTIR 8107, National Institute of Standards and Technology, Gaithersburg. https://doi.org/10.6028/NIST.IR.8107

Mittal, S., Romero, D., & Wuest, T. (2018). Towards a Smart Manufacturing Maturity Model for SMEs (SM 3 E). In *IFIP International Conference on Advances in Production Management Systems* (155-163). Springer, Cham. https://doi.org/10.1007/978-3-319-99707-0_20

OECD (2019). *OECD SME and Entrepreneurship Outlook 2019.* OECD Publishing, Paris. https://doi.org/10.1787/34907e9c-en

Oztemel E., & Gursev, S. (2020). A taxonomy of Industry 4.0 and related technologies In Hamilton-Ortiz, J. (Ed.), *Industry 4.0. Current status and future trends.* IntechOpen. Available at: https://www.intechopen.com/books/industry-4-0-current-status-and-future-trends

Pöppelbuß, J., & Röglinger, M. (2011). What makes a useful maturity model? A framework of general design principles for maturity models and its demonstration in business process management. *ECIS 2011 Proceedings* (28). Available at: https://aisel.aisnet.org/ecis2011/28

Rauch, E., Unterhofer, M., Rojas, R., Gualtieri, L., Woschank, M., & Matt, D. (2020). A Maturity Level-Based Assessment Tool to Enhance the Implementation of Industry 4.0 in Small and Medium-Sized Enterprises. *Sustainability,* 12, 3559. https://doi.org/10.3390/su12093559

Ravinder, K., Rajesh, K., Singh, Y, & Dwivedi, K. (2020). Application of industry 4.0 technologies in SMEs for ethical and sustainable operations: Analysis of challenges. *Journal of Cleaner Production,* 275. https://doi.org/10.1016/j.jclepro.2020.124063

SAIN4 (2016). *Informe sobre el Estado del Arte de la Industria 4.0.* Proyectos de I+D en colaboración. Available at: http://intranet.aidimme.es/acceso_externo/difusion_proyectos/adjuntos_resultados/E1.1_COLAB_SAIN4_IMDECA201635_AIDIMME_2016.pdf

Schumacher, A., Erol, S., & Sihn, W. (2016). A Maturity Model for Assessing Industry 4.0 Readiness and Maturity of Manufacturing Enterprises. *Procedia CIRP* 52, 161-166. https://doi.org/10.1016/j.procir.2016.07.040

Singh, R.K., & Kumar, R. (2020). Strategic issues in supply chain management of Indian SMEs due to globalization: an empirical study. *Benchmark an International Journal,* 27 (3), 913-932. https://doi.org/10.1108/BIJ-09-2019-0429

Smart Manufacturing Leadership Coalition (2011). *Implementing 21st Century Smart Manufacturing: Workshop Summary Report.* Washington D.C. Available at: https://www.controlglobal.com/assets/11WPpdf/110621_SMLC-smart-manufacturing.pdf

Thoben, K., Wiesner, S., & Wuest, T. (2017). "Industrie 4.0" and Smart Manufacturing – A Review of Research Issues and Application Examples. *International Journal of Automation Technology*, 11(1), 4-16. https://doi.org/10.20965/ijat.2017.p0004

Wagire, A., Joshi R., Rathore, A.P.S.,& Jain, R. (2020). Development of Maturity Model for Assessing the Implementation of Industry 4.0: Learning from Theory and Practice. Production Planning and Control, 32(8), 603-622. https://doi.org/10.1080/09537287.2020.1744763

Weber, C., Königsberger, J., Kassner, L., & Mitschang, B. (2017). M2DDM - A maturity model for data-driven manufacturing. *Procedia CIRP,* 63, 173-178. https://doi.org/10.1016/j.procir.2017.03.309

World Economic Forum (2016). *Digital Transformation of Industries: Digital enterprise.* White Paper. Available at: http://reports.weforum.org/digital-transformation/wp-content/blogs.dir/94/mp/files/pages/files/dti-digital-enterprise-white-paper.pdf

Zheng, P., Wang, H., Sang, Z., & Zhong, R. (2018). Smart manufacturing systems for Industry 4.0: Conceptual framework, scenarios, and future perspectives. *Frontiers of Mechanical Engineering,* 13(2), 137-150. https://doi.org/10.1007/s11465-018-0499-5

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