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Evaluation of the degree of implementation of Industry 4.0 technologies in metalworking SMEs using the IMPULS maturity model

Evaluación del grado de implementación de tecnologías Industria 4.0 en pymes metalmecánicas mediante el modelo de madurez IMPULS

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Abstract: This study evaluates maturity in the digital transformation of SMEs of the metalworking sector in Boyacá, Colombia, using the promotion model. With a sample of 24 SMEs, a questionnaire was applied to analyze six key dimensions of digitalization. The results show that 83% of the companies are at initial maturity levels, and only 16.4% reaches a level of beginners. The main barriers identified are the lack of financial resources, poor digital infrastructure and low data -based services integration. To move towards a sustainable and competitive digital transformation, it is essential to strengthen digital strategies, human talent and technological infrastructure.

Keywords: Industry 4.0, SMEs, digital transformation, maturity in industry 4.0, Impuls.

Resumen: Este estudio evalúa la madurez en la transformación digital de las Pymes del sector metalmecánico en Boyacá, Colombia, usando el modelo IMPULS. Con una muestra de 24 Pymes, se aplicó un cuestionario para analizar seis dimensiones clave de la digitalización. Los resultados muestran que el 83% de las empresas están en niveles iniciales de madurez, y solo el 16.4% alcanza un nivel de principiantes. Las principales barreras identificadas son la falta de recursos financieros, infraestructura digital deficiente y baja integración de servicios basados en datos. Para avanzar hacia una transformación digital sostenible y competitiva, es esencial fortalecer las estrategias digitales, el talento humano y la infraestructura tecnológica.

Palabras clave: Industria 4.0, Pymes, transformación digital, madurez en industria 4.0, Impuls.

1. INTRODUCTION

Since the beginning of the 21st century, the concept of the fourth industrial revolution has been introduced to define the integration of automation with advanced digital technologies such as Artificial Intelligence (AI), blockchain, Internet of Things (IoT), collaborative robots, Big Data, cloud computing and other state-of-the-art information and communications technologies (ICT). The concept of Industry 4.0 was used for the first time in 2011 at the Hannover-Messe Technology Fair in Germany to refer to the digitalization of industrial systems and processes and their integration with IoT through the internet in order to improve the flexibility of production processes, then other advances in disruptive ICTs such as cloud computing were incorporated. Big Data and cybersecurity in a smart factory vision [1], [2], [3].

Smart manufacturing has generated new conditions that frame the development, transformation and modernization of the global economy, generating in which industrial companies are immersed. In the process of digital business digitalization, large companies have a comparative advantage in relation to Small and Medium-sized Enterprises (SMEs) which, due to the scarcity of financing, technological deficiencies, little awareness of transformation and lack of competent human talent, are faced with greater problems in the implementation of business digitalization [1]. It should be noted that Industry 4.0 arises with the aim of increasing productivity in the manufacturing sector, where its application allows companies to better adapt to the needs of customers by customizing production, while optimizing processes and reducing manufacturing times and costs.

The cyber-physical systems that make up smart factories are configurations that combine physical and computing capabilities, interacting through data networks, and in the case of Industry 4.0 they are essential, as they comprise intelligent machines and storage systems that can operate autonomously [4]. These cyber-physical systems can exchange information, initiate actions, and independently controlling each other, enabling significant optimizations in industrial processes such as manufacturing, material use, and product lifecycle management [4], [5].

Within the framework of industry 4.0, digitalization is defined as the use of digital technologies in organizations with the purpose of generating value and increasing the range of revenue, for which a change in the business model is necessary [6], [7]. The use of these digital technologies (Big Data, IoT, social networks, cloud computing, AI) in the usual processes and operations of companies generate important changes and impacts on their structures, this evolution is known as digital transformation of organizations [8], [9], [10]. An adequate and comprehensive framework for the digital transformation of organizations must include both business management and operations, including critical success factors such as technology, human talent, and strategy. [11], [12].

According to the United Nations Industrial Development Organization's Industrial Development Report, Industry 4.0 technologies are reshaping the way people live and work, offering innovative solutions that can help overcome global challenges and move towards more inclusive and sustainable development [13]. For SMEs to be integrated into the global economy, it is necessary for them to implement these industry 4.0 technologies, however, they face important challenges such as resource restrictions, limitations on access to cutting-edge technologies and human capital with knowledge and experience restrictions in analysis and implementation of the elements that make up industry 4.0 [14], [15]. Therefore, to evaluate organizational digital transformation, it is necessary to consider both strategic and operational aspects [13]. Regarding the evaluation of the degree of maturity in digital transformation, SMEs must consider both technology and processes, using key indicators such as organizational strategy, implementation roadmap, technology and human talent in order to obtain a comprehensive assessment [11].

Digital transformation is necessary for SMEs that want to harness the immense potential of these technologies to expand the market and foster long-term sustainable growth [16]. However, the challenges of digital transformation in SMEs are significant considering that they must build dynamic capacities that allow them to adapt, innovate and take advantage of new market opportunities while effectively managing their limited resources. A study on SMEs in Malaysia recommends that managers prioritize the incorporation of Industry 4.0 technologies into their processes and operations and promote the ability to adapt to rapid changes in the global market to achieve better performance in the international arena [16].

A study of manufacturing SMEs in the province of Guangdong in China showed that the

implementation of information and communication technologies of industry 4.0 and the digital strategy are key factors in the digital transformation of SMEs, in addition this study managed to identify that the main problems faced by these small and medium-sized enterprises are related to digital innovation and digital processes themselves [1]. While an analysis of the level of maturity in industry 4.0 in Turkey using an unprecedented model managed to establish that the main obstacle to the digitalization of industrial companies corresponds to the lack of trained human talent in the use of these digital technologies, in addition, the study identified as important obstacles in the digital transformation of these companies financial insufficiency and uncertainty in the return on the necessary investment in these technologies and in the modernization of the business model [17].

These last two obstacles to the digital transformation of Industry 4.0 related to the high costs of technology and the uncertainty of the return on investment are supported in the case of SMEs by [18]. A study of SMEs in the manufacturing sector in Europe and the United Kingdom concluded that the low level of implementation of Industry 4.0 in SMEs is a complex and multidimensional challenge involving technological, organizational and environmental variables. On the one hand, many of these SMEs fail to take advantage of the full potential of new technologies because they lack capacities, infrastructure and skills in information technology. On the other hand, when organizational factors are lacking, the capacity for digital transformation also decreases [18]. Therefore, it is essential that SMEs pay attention to both the technological part and the internal organization to advance in the implementation of Industry 4.0 and not be left behind in a competitive and globalized market.

A study of SMEs in Italy provides guidance on how these companies can guide their digital transformation 4.0 path at each stage of the supply chain and highlights the importance of collaborative work between the triple helix to identify and take advantage of digital opportunities. IoT, Big Data and simulation made up the three groups of digital opportunities that positively impact the degree of adoption of 4.0 technologies, in the design phase actions aimed at improving cybersecurity are relevant, in the production phase the relevant digital opportunity corresponds to collaborative robots and in the product/service innovation phase the adoption of augmented and virtual reality technologies is important [19].

In the environment of Industry 4.0, SMEs are faced with great challenges to guarantee the sustainability of their production processes. A study of industrial SMEs in Brazil managed to recognize that the organization of the production process, the permanent development of skills in employees, and the simplification of production planning and control are critical factors to take advantage of 4.0 technologies to make their manufacturing operations more sustainable [20]. Therefore, it is important to invest in Industry 4 technologies to support these functions and achieve improvements in the operational efficiency and long-term performance of SMEs.

Some studies reveal how the implementation of structured methodologies improves operational efficiency in metalworking SMEs. An SME in Lima - Peru, which applied the lean methodology to overcome an efficiency deficit. By using Business Process Management (BPM) tools, Holt-Winter forecasting, and an inventory model optimized through the DMAIC (Define, Measure, Analyze, Improve, Control) process, the company was able to increase its operational efficiency from 77% to 90%, the increase in productivity and inventory optimization [21]. This study demonstrates how structured practices can facilitate the adoption of industry 4.0 technologies, highlighting the importance of these methodologies to improve competitiveness in the metalworking industry.

An analysis of the implementation of Industry 4.0 technologies in the manufacturing sector of Ciudad Juárez, Mexico, evaluated their impact on production efficiency and labor well-being, including aspects such as wages and working conditions. Through a PLS structural equation model, the study identified that although the level of knowledge and implementation of these technologies is generally low in SMEs, companies that have adopted them report significant improvements in productivity and working conditions, which highlights the relevance of Industry 4.0 in both improving efficiency and worker well-being [22].

Recent literature related to maturity levels in Industry 4.0 seeks to relate aspects such as digital technologies and corporate strategy to topics such as business model innovation, global supply chains, collaboration and corporate performance [23]. Most of the studies related to models to determine the levels of maturity in industry 4.0 have focused on large companies, leaving a gap in the literature

regarding the impacts of these maturity models on the management, organization and infrastructure of industry 4.0 in SMEs [23]. This gap in the scientific literature gives relevance to this study focused on the levels of maturity in industry 4.0 in SMEs in Colombia.

Colombia is no stranger to the impacts of these technological advances of the fourth industrial revolution, making necessary a radical transformation in the production processes in the Colombian conventional industry and generating the challenge of integrating new digital technologies to innovate in products and in logistics and marketing strategies [24]. In the Colombian context, several studies have been carried out related to maturity in industry 4.0 in SMEs. Regarding the adoption of strategies and technologies in manufacturing SMEs in Bogotá, it has been identified that 85% do not carry out training in these technological tools, only 18.6% have an investment plan to implement them, 3.9% use specialized software for data processing and 36.3% do not use any cybersecurity method [25]. This shows a considerable gap in the adoption of advanced technologies, limiting the competitiveness and efficiency of SMEs in an increasingly globalized and technologically advanced market.

Likewise, the incorporation of Industry 4.0 technologies in the metalworking sector of Barranquilla - Colombia, has made it possible to overcome significant traditional operational barriers, where they highlight how advanced automation and the use of welding robots, guided by fuzzy logic and controlled through real-time sensory systems, have drastically improved the precision and efficiency of manufacturing processes [26]. The implementation of these technologies has optimized the routes and movements of the robots to improve the welding trajectory, facilitating the adaptation of operations to the specific challenges of accessibility and configuration of the machines, thus providing customized solutions that reinforce the competitiveness of the sector in the global arena.

An analysis related to the integration of Industry 4.0 technologies in 121 Colombian SMEs in the manufacturing, services and agricultural sectors, managed to identify a low widespread adoption of Industry 4.0 and highlight common challenges such as lack of adequate infrastructure and high investment costs, particular problems such as cybersecurity and resistance to change were also determined as significant obstacles in the transformation process digital [27].

The main purpose of this research project was to identify the level of adoption of Industry 4.0 technologies and processes in SMEs in the metalworking manufacturing sector in Boyacá – Colombia. Through an analysis, they identified barriers that hinder such adoption and the opportunities that arise to boost the local economy and improve the operational efficiency of this type of company. The project is based on the industry 4.0 maturity model known as IMPULS, which was developed by IW Consult and the Institute of Industrial Management (FIR) of RWTH Aachen University, on behalf of the Impuls Foundation of the German Engineering Federation (VDMA).

2. METHODOLOGY

This empirical research focuses on determining the level of maturity in industry 4 of SMEs in the metalworking sector of the industrial corridor sector of Boyacá Colombia. The maturity model used in this research corresponds to the IMPULS model developed by the German Association of Mechanical Engineers [28]. The IMPULS - Industrie 4.0 Readiness model was developed to assess the readiness of companies, especially in mechanical engineering and plant manufacturing, to adopt Industry 4.0 technologies, seeking to provide a detailed and systematic diagnosis on the degree of readiness of companies to integrate these technologies into their operational and strategic processes [29]. This model classifies firms into the six maturity levels illustrated in Figure 1.

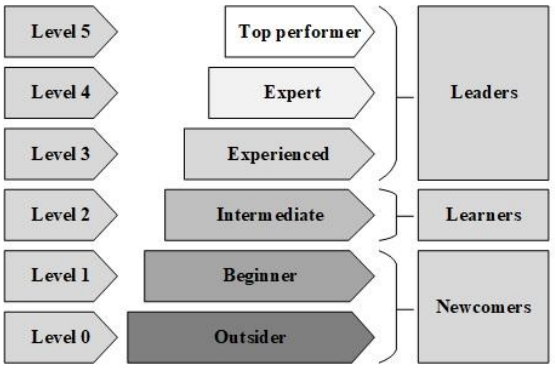

***Fig. 1**. Maturity levels of the IMPULS model.*
***Source:** [29].*

The classification into the maturity levels of the IMPULS model is carried out by evaluating key indicators in the six critical dimensions presented in Table 1.

Table 1: *Maturity dimensions of the IMPULS model*

Dimension	Aspects it evaluates
1. Strategy and organization	Degree of implementation of Industry 4.0 in the company's strategy.
2. Smart factory	Level of automated and digitally integrated production based on cyber-physical systems.
3. Smart Operations	The degree to which processes and products are digitally modelled and can be controlled through ICT systems and algorithms in a virtual world.
4. Smart Products	Control products with IT, allowing them to communicate and interact with higher-level systems along the value chain.
5. Data-driven services	Offering data-driven services that are only possible through the integration of products, production, and customers.
6. Employees	Skills needed to implement Industry 4.0 concepts.

The type of sampling used in this study was for convenience, considering that the information collected turned out to be confidential for some of the SMEs in the metalworking sector of Boyacá – Colombia. The sample size was 24 SMEs to whom the IMPULS model questionnaire was applied. The data collected were analyzed according to the evaluation criteria established by the industry 4.0 maturity model selected for the purpose of classifying organizations in one of the six maturity levels and identifying the main particular barriers of these SMEs in their digital transformation 4.0 process.

Non-probability convenience sampling, while limiting the ability to generalize results, is particularly valuable in research where conditions do not allow for probability sampling. It has been used extensively in exploratory studies that seek to develop hypotheses or preliminary insights in specific contexts, where the accessibility and disposition of study subjects can be challenging [31]. The application of this approach allowed an immersion in the specific realities of SMEs that were willing to share detailed and relevant information related to their digital transformation process in the context of industry 4.0.

3. RESULTS

When evaluating the level of maturity in Industry 4.0 of SMEs in the metalworking manufacturing sector in Boyacá with the IMPULS model, it was possible to classify these companies according to the levels established by the model, the results are illustrated in Figure 2. As can be seen in Figure 2, 12.5% of SMEs were classified in 0, which corresponds to those that have not started their digital transformation process; 70.8% of SMEs were classified as Beginners; only 16.7% of these SMEs were located at maturity level 3, which corresponds to intermediate in the adoption and application of Industry 4.0 technologies. It is noteworthy that none of the SMEs managed to be classified as experienced, expert or top performer, which correspond to the three highest levels of maturity in Industry 4.0, making evident the need for interventions to advance towards higher levels of maturity, taking advantage of the opportunities offered by Industry 4.0 to improve their competitiveness in the global economic environment.

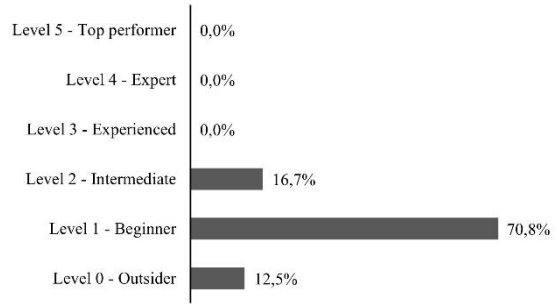

Fig. 2*. Classification of Boyacá SMEs in the maturity levels of the IMPULS model.*
Source: *[30].*

The quantitative analysis of the general maturity level for this group of industrial SMEs in the metalworking sector by dimensions of the IMPULS model is presented in Table 2, where the general averages are related both for the six dimensions and for each of the factors that comprise each of these dimensions of maturity in industry 4.0.

Table 2: *Analysis of maturity dimensions for SMEs*

Dimension	Average Dimension	Factor	Average Factor
Strategy and organization	1,4	Status of implementation of the Industry 4.0 strategy	1,4
		Industry 4.0-related investments	1,2
		Use of technology and innovation management	1,6
Smart factory	1,5	Digital Modelling	1
		Equipment and infrastructure	1,7
		Data usage	1,5
		IT Systems	1,8
Smart Operations	2,2	Using Cloud Computing	3

		IT Security	2,5
		Autonomous processes	1,8
		Information exchange	1,5
Smart Products	1,1	Data analysis in the use phase	1,2
		Complementary ICT functionalities	1
Data-driven services	1	Proportion of data used	1
		Share of revenue derived from data-driven services	1
		Availability of data-driven services	1
Employees	1,4	Efforts by the company to acquire new skills.	1,4
		Employee competencies	1,4

As for the first dimension, it is considered that Industry 4.0 goes beyond technological aspects, generating opportunities to develop a new business model. As can be seen in Table 2, when evaluating the strategy dimension, very low scores are obtained, indicating that these SMEs need a roadmap for the implementation of the Industry 4.0 strategy that contemplates the operationalization and review of the strategy through a system of indicators. It should be noted that the main obstacle in this dimension corresponds to investment due to the limited resources of these SMEs and the difficulties in obtaining financing.

Dimension 2, related to smart factory, considers cyber-physical systems (CFS), which connect the physical and virtual worlds through communication through an IT infrastructure. As can be seen in the results of table 2, at a general level, the maturity of these SMEs in the metalworking sector of Boyacá is at level 1 as beginners in relation to smart factory indicators. This result highlights the need to implement strategies to achieve digital modelling through the collection, storage and intelligent processing of data in the production process of these SMEs, which is the factor with the lowest score within this dimension. It also highlights the deficient real-time inter-company collaboration between production systems, ICTs and people in these SMEs. It is necessary to implement strategies that guarantee this collaboration and the processing and analysis of data for decision-making.

The third dimension of the maturity model is intelligent operations, which refers to the technical production and production planning requirements necessary to achieve the self-controlled workpiece. For the SMEs analyzed, this dimension was the one with the highest score, placing them in general at level 2 or intermediate. This result indicates that the emphasis on the elements of industry 4.0 by SMEs in the metalworking sector of Boyacá is oriented to the technical aspects related to information systems, IoT and cloud computing to make their production planning systems (PPS) and supply chain management (SCM) more efficient.

The fourth dimension of the IMPULS model relates to the ability of products to collect data, know their production process and communicate with higher-level systems in order to improve and guide production processes autonomously and in real time. This dimension of smart products was one of the lowest overall scores in the group of SMEs analyzed, therefore, in order to advance in the maturity of digital transformation 4.0, these companies must incorporate complementary ICT functionalities in their products in such a way that their status can be monitored and data analysis incorporated in the use phase.

The fifth dimension of this maturity model in industry 4.0 corresponds to data-based services and was the lowest overall score for the group of SMEs participating in this study. This result indicates that these SMEs, by not having data on their products in the use phase, lose the opportunity to incorporate business models and optimize the benefits for the customer by improving after-sales based on the analysis of the data collected from the products placed on the market. Finally, the sixth dimension of maturity of the IMPULS model is related to the degree of implementation of strategies by SMEs to prepare their employees to efficiently face the labor changes of the industry 4.0 work environment. The overall score for the group of SMEs analyzed in this study places them at the beginner level.

4. CONCLUSIONS

When analyzing the digital transformation process, in the context of industry 4.0, of a group of industrial SMEs in the metalworking sector of Boyacá – Colombia, it was evident that the efforts of these organizations in the strategic aspects of industry 4.0 and operational are incipient. This is considering that more than 83% of the SMEs that participated in this study were located at levels 0 and 1 of maturity in industry 4.0 according to the criteria of the IMPULS model. Only 16.7% of these SMEs were classified in the 2 or intermediate of this maturity model. It should be noted that SMEs classified at the

intermediate level correspond to companies that compete in the national and international markets, while SMEs classified at the lowest levels of the model compete in the Colombian regional market.

Within the six dimensions of maturity in industry 4.0 that make up the IMPULS model, the best rated in this group of SMEs in the metalworking sector was Intelligent Operations. This result allows us to affirm that these SMEs have been oriented preferably to the implementation of technical requirements for the planning and control of production and logistics in search of the integration of the physical and the virtual in these processes. Within the dimension of intelligent operations, the technical aspects most used by this group of SMEs correspond to the use of cloud computing and computer security systems. This without forgetting that the group of SMEs in general are mostly ranked as beginners in their digital transformation process in industry 4.0, according to the results of applying the IMPULS model:

As dimensions of maturity in industry 4.0 with the lowest score in this group of SMEs, intelligent products and data-based services stand out. This result reflects the deficiency of these SMEs to achieve automated, flexible and efficient production, highlighting that they must look for strategies to integrate ICT components into products with the aim of collecting data on their environment and their own state to improve communication between customers and manufacturers. Likewise, it is important for these SMEs to advance in their business digitalization process in collecting post-sales data in search of optimizing the benefits for the customer and to start a process of business integration in their supply chain.

Obstacles to advancing in the digital transformation of these SMEs in the metalworking sector include: 1) the low investment due to the limited resources of these companies and their difficulty in obtaining financing; 2) the lack of digital modeling systems that allow the collection, processing and intelligent analysis of data at each stage of the production process through cyber-physical systems; 3) the lack of incorporation of ICT complements in products for the generation and analysis of data focused on improving communication in the supply chain and the customer experience and; 4) The lack of a comprehensive vision of Industry 4.0 as an opportunity to develop a new business model that, in addition to improving existing products and processes, opens the possibility of a new organizational culture that is oriented towards efficiency and competitiveness in a global environment characterized by digitalization.

Finally, the authors make explicit the limitations related to sample size and convenience sample design. These limitations call for caution when generating generalizations of the results obtained in this study.

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