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Industry 4.0 readiness model designed for public research centers and universities

Modelo de preparación para Industria 4.0 diseñado para centros de investigación públicos y universidades

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Abstract

In this research, a quantitative diagnostic instrument was developed to evaluate the technological capabilities that public research centers and universities must develop projects related to Industry 4.0 technologies. Because the characteristics and development objectives of projects carried out in an academic environment differ from those developed within an industrial environment, the diagnostic instruments found in the literature cannot be fully applied to academic projects. This research aimed to develop a model that focuses on studying the technological dimensions, as well as the capabilities of people framed in an academic field, leaving aside the areas related to products and businesses. The questionnaire developed was answered by researchers who work in Mexican institutions and who are in charge of research related to technology. The readiness model developed evaluates the three dimensions that are common to industry and academia: personnel, manufacturing and functions based on the collected data. The proposed model can be used to identify areas that need to be reinforced when working on technological projects.

Keywords: industria 4.0, modelo de referencia de I4.0, transformación digital, academia

Resumen

En esta investigación se desarrolló un instrumento cuantitativo de diagnóstico para evaluar las capacidades tecnológicas que los centros públicos de investigación y las universidades poseen para desarrollar proyectos relacionados con tecnologías de la Industria 4.0. Debido a que las características y objetivos de desarrollo de los proyectos realizados en un ambiente académico difieren de aquellos desarrollados dentro de un ambiente industrial, los instrumentos de diagnóstico encontrados en la literatura no pueden aplicarse plenamente a proyectos académicos. Esta investigación tuvo como objetivo desarrollar un modelo que se centre en estudiar las dimensiones tecnológicas, así como las capacidades de las personas enmarcadas en un ámbito académico, dejando de lado las áreas relativas a productos y negocios. El cuestionario desarrollado fue respondido por investigadores que trabajan en instituciones mexicanas y quienes están a cargo de investigaciones relacionadas con la tecnología. El modelo de preparación desarrollado evalúa las tres dimensiones que son comunes a la industria y la academia: personal, fabricación y funciones basadas en los datos recopilados. El modelo propuesto puede ser usado para identificar áreas que necesitan ser reforzadas al trabajar en proyectos tecnológicos.

Palabras clave: industry 4.0, reference model for I4.0, digital transformation, academy

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1. Introduction

Since the introduction of the term Industry 4.0 (I4.0) to designate a manufacturing system that integrates the physical world with the digital, assessment instruments have been designed to allow companies to measure their capabilities to integrate new technologies into their value, supply and production chains. In general, the developed assessment models can be divided into those that allow companies to measure the level of technological integration, those measuring the company's capabilities to change its production processes, towards an I4.0 model called models of capability maturity, and models that define steps to enable the company to reach a certain integration goal called procedural models (Pessl et al., 2017). Within those assessing technological integration, there are models in the literature that can be subclassified into two main categories: those that evaluate various I4.0 technologies, called holistic methods, and those that focus on a single technical aspect at a very detailed level, known as specific methods (Schumacher et al., 2019).

Despite the varying characteristics of methodologies found in the literature, two common aspects utilized for generating a measure of integration or maturity are the dimensions and elements. Dimensions are areas of specific capabilities, process areas or design objects that structure the field of interest and the elements refer to aspects of each dimension (practices or activities) that must be analyzed individually (De Carolis et al., 2017; Rafael et al., 2020). For example, one dimension can be quality management and within the elements that would be evaluated in it are the level of digitalization in product tests and in production quality. Most of the methods found in the literature are adapted to measure dimensions typically found in a business environment (Akdil et al., 2018; Butt, 2020; Ghobakhloo, 2018; Hizam-Hanafiah et al., 2020; Pessl et al., 2017; Schumacher et al., 2019) –intelligent supply chain management, intelligent marketing strategies, strategy for hiring highly skilled human resources, regulations and operation standards of I4.0–, some others focus on a single type of industry (Arden et al., 2021; Bibby & Dehe, 2018; Mayusda & Wiratmadja, 2020; Stawiarska et al., 2021). A large number of countries have proposed integration methodologies and roadmaps tailored to local industry, such as those developed by the Federal Ministry for Economic Affairs and Energy in Germany (Plattform Industrie 4.0, 2019) or the Industry 4.0 National Plan in Italy (Bruschieri & Rizzi, 2019), a couple of examples among many. However, when trying to apply these models to an academic environment, problems arise since not all the dimensions that are qualified in a company setting exist within the environment in which a technological project is developed in research stages. For instance, in Amaral & Peças (2021) and Arden & Doucek (2019) authors found that many maturity evaluation frameworks focus on enterprise management dimensions such as strategy, corporate culture, human resources, product, and governance, and when measuring the technology dimension some aim the questions to large enterprises, such as warehouse management technologies. Said dimensions are rarely seen in the academic research environment.

The aim of this research is to develop a quantitative diagnostic instrument to measure different aspects of a project: a) the current situation in terms of the level of integration of I4.0 technologies, b) the capabilities of developing I4.0 related projects of the research centers and universities, c) it will help to identify the gap between

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the technologies incorporated in their current research and the technologies needed to achieve the objective, and d) it will serve as a self-assessment framework for universities. The method used will be called semi-holistic, since it will focus on technologies that are currently being designed as "Industry 4.0 supporting technologies" (Jamwal et al., 2021; Oztemel & Gursev, 2020). The proposed framework is flexible in regard of the technologies needed, due to the broad areas of research, and the final objective, considering that in academia the final goal might be a simulation stage, to manufacture of prototype, or intended to provide a service. The latter features give rise to an evaluation tool with a wide area of application within the academic community.

2. Method of research

2.1. Questionnaire design

The instrument for measuring the integration of Industry 4.0 related technologies in academic projects is a questionnaire with closed questions that allow quick responses for participants, resulting in precise information for further analysis. The developed instrument is based on models from PwC Consulting Group (Geissbauer et al., 2016), the IMPULS Foundation of the German Engineering Federation (IMPULS, 2015) and the "Industry 4.0 Readiness Assessment Tool" (Agca et al., 2021). Each of these evaluates dimensions that are common in a business environment, but they also focus on technological areas. In Tables 1, 2 and 3 these dimensions and sub-dimensions for IMPULS and Warwick are shown. The latter models, chosen for their availability of information and consideration of a technology dimension expanding to the manufacturing process (in the case of IMPULS and Warwick frameworks), also consider a dimension highlighting employees' capabilities.

Table 1

Dimensions and sub-dimensions of the IMPULS model

Dimension	Subdimension
1. Employees	Employees' capabilities, capability acquisition
2. Strategy and organization	Strategy, inversion, innovation, management
3. Smart industry	Digital modeling, infrastructure, data usage
4. Smart operation	Cloud usage, Information Technology (IT) security, autonomous processes
5. Smart product	Information and Communication Technologies (ICT) functions, data analysis in real time
6. Data services	Added services, revenue shares, data usage

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Table 2

Dimensions of the PwC model

Dimension
1. Business model, products and services portfolio
2. Market and consumer access
3. Value chains and processess
4. IT architcture
5. Compliance, legal, risk, security and taxes
6. Organization and culture

Table 3

Dimensions and sub-dimensions of the IMPULS model

Dimension	Subdimension
1. Products & services	Customization, digital features, services based on data, revenue shares
2. Manufacturing & Operation	Automatization, machine-machine integration (M2M), equipment readiness for I4.0 autonomously guided parts, automatically optimized processes, digital modeling, data collection, data usage, cloud solutions, IT and data security.
3. Strategy & Organization	Degree of implementation, measurements, investment, people skills, collaboration, leadership, finances
4. Supply chain	Real-time inventory control, integration, visibility and flexibility of the supply chain, waiting times
5. Business Model	Business model “as a service”, decision making based on data, real-time automated planning, integrated marketing channels, IT-based business
6. Legal considerations	Hiring, risk, data protection, intellectual property.

In the proposed model, the dimensions aimed to evaluate management, products, business, and legal aspects will be dropped, considering only the following: a) Personnel, b) Manufacturing and Operations, and c) Data-Driven Functions. The proposed assessment framework considers a Manufacturing and Operations dimension. However, considering that a project being developed by researchers may not be aimed at reaching a production stage or may be tied to a budget that will only allow reaching certain stages of development, parts of this dimension will not be considered if the participant states that the project is not intended to be built.

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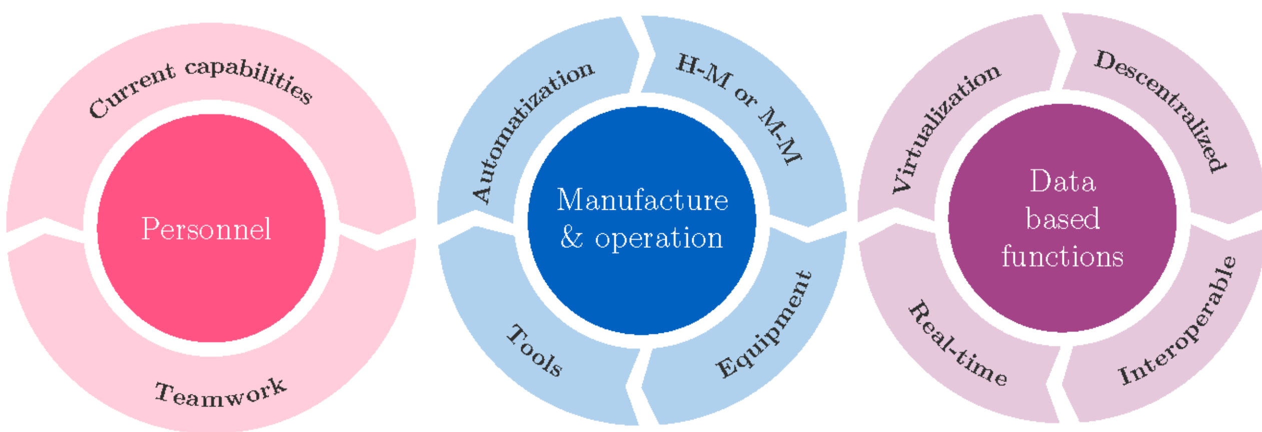
The first dimension, *Personnel*, focuses on the individuals involved in the project. Due to the high degree of specialization found in academia, interdisciplinary collaboration is common in large-scale projects. Depending on the project's objectives, it may be necessary to collaborate with individuals possessing different skills or to undergo training to acquire additional abilities. As the project grows larger, the need for managing information from various sources and employing efficient communication tools increases. Hence, the sub-dimensions to be evaluated include the Current skills of the personnel directly involved in the project and the Collaboration with different institutes or industries. Figure 1 visualizes the latter proposition. The assessment will consider the project's size, the methods employed for personnel to acquire new capabilities, and the number of personnel required for development, through open-ended or multiple-selection questions.

The second dimension, *Manufacturing and Operation*, focuses on the technological aspects used to develop and operate the project. These areas were selected because they are commonly associated in literature with Industry 4.0 in manufacturing (Jamwal et al., 2021); and they are also expected to have a major impact on the future of industry. The chosen technology areas will serve as sub-dimensions to measure integration, the considered ones are: Human-Machine (H-M) Integration, Manufacture, Parts and tools management, and Automation (Figure 1).

Figure 1

Dimensions and subdimensions of the proposed model. (a) Personnel, (b) Manufacture and operation, (c) Data based functionalities (respectively)



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The latter fields have enabling technologies that are common to each other, such as Big Data, Cloud Computing (CC), Systems Integration (ΣI), Artificial Intelligence (AI), Internet of Things (IoT) and Simulation (Table 4). The instrument will consider the scope of each project to issue an evaluation, since, as previously stated, the research objective is not always to reach a development phase, even less to provide continuous service.

Table 4

Areas and related technologies

Dimensiones	Big Data	CC	Σ I	AI	IoT	Simulation
1. H-M Integration	X	X	X	X	X	
2. Manufacture	X	X		X	X	X
3. Parts & tools management	X	X	X	X	X	X
4. Automation	X	X	X	X	X	

In the third dimension, Data-Driven Functions, the operating principles linked to information collection and utilization, which are most commonly cited in the literature (Bousdekis et al., 2021), will be identified and measured according to the level of integration of technologies relying on data usage. This includes assessing how much information is collected by different means (such as sensors, databases, and human sources) and whether the gathered data is being used for any design purpose. Below, the operating principles to be evaluated are listed and described; they will serve as sub-dimensions for the developed framework.

- *Decentralization*. Defined as the ability of a system to make decisions and execute actions autonomously, it provides flexibility and can improve productivity (Zhang et al., 2017). The technologies on which decentralization is supported are IoT, AI, Big Data, Cloud Computing, among others.
- *Interoperability*. Refers to the ability to exchange information and make use of it between two or more systems or components. Information exchange can occur between humans (H-H), between humans and machines (H-M), or between machines (M-M) without human intervention. The enabling technologies for interoperability are IoT and Big Data (Jirkovskỳ et al., 2016).

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- *Real-time management*. Encompasses the ability of a system to collect, analyze and transfer information in real time (Hermann et al., 2016). This ability can speed up decision-making, identify or predict failures in system components or determine optimization opportunities. It is supported by Big Data, Cloud Computing and IoT.
- *Virtualization*. Also known as Digital Twin, it is understood as the representation of the characteristics and behavior of a physical system in a virtual environment. It comprises three entities: systems in the physical world, those in the digital or virtual world, and the data connecting them (Qi & Tao, 2018). In the virtual environment, data is collected and analyzed to make predictions and enrich decision-making, it is mainly supported by Simulation, Big Data and IoT.

2.2. Questionnaire application

The instrument is intended for researchers working in universities and research centers, responsible for projects tailored for an industrial setting. The application of the questionnaire was divided in two stages, the objective of the first stage was to select a small group of people who could provide feedback to improve the instrument. The second stage was aimed to reach a larger group of people to collect the data and form a database of projects (only those who consent to share information). The results presented in this article are from the conclusion of the first stage, after the initial group of participants answered, provided feedback, and their suggestions were integrated to develop the current questionnaire. Invitations to participate were sent to 10 researchers working in institutions (both universities and research centers were considered) located in different Mexican states (Aguascalientes, Guanajuato, Nuevo León, Querétaro, and San Luis Potosí). Eight colleagues responded to the invitation; however, two responses were not considered: one project was already finished, and the other did not meet the criteria. Therefore, the answers and feedback from six individuals were considered to develop the final form of the proposed measurement framework.

2.3. Measurement of results

The developed instrument consists of 54 questions and sub-questions divided in two sections. The first section, consisting of 11 questions, serves as a general information section, while the second section aims to evaluate the proposed sub-dimensions. The general information section consists of open-answer and multiple-selection questions, aimed at providing an overview of the project. The remaining 43 questions, targeted for analyzing the dimensions, are closed-ended. A Likert scale will be used to measure each sub-dimension at four levels: *Beginner*, *Intermediate*, *Experienced* and *Expert*, plus an option *Not necessary*, if the evaluated dimension is not necessary for the project development. The scale ranges from 1 (assigned to the beginner level) to 4 (indicating total expertise in the implementation). Zero points will be given when the measured sub-dimension is not required,

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and in such scenario, it will not be considered for the evaluation. The Likert scale was chosen for its ease of design and implementation, quick and simple response format, and its ability to serve as a comparison of previous evaluations if the user wishes to retake the test after improving or advancing the development of the project.

For the proposed dimensions, the points required to reach each level are distributed as shown in Table 5. The sub-dimensions contribute points in equal proportion to the dimension they are embedded in. For instance, the *Personnel* dimension consists of two sub-dimensions, each of which may have a maximum of 32 points. When both are added, the total of 64 points is obtained.

Table 5

Maximum points that can be obtained

	Beginner 25%	Intermediate 50%	Experienced 75%	Expert 100%
1. Personnel	1 – 16	17 - 32	33 – 48	49 – 64
2. Manufacture & Operations	1 – 16	17 – 32	33 – 48	49 – 64
3. Data-driven functions	1 – 12	13 – 24	25 – 36	37 – 48

3. Proposed diagnostic instrument

3.1. General questions

The proposed instrument begins with an optional answer section where participant may provide additional significant information about their project, such as its name, the number of people working on it, and the technological area to which it is addressed. In future research stages, the data in this section may serve as a catalog depicting projects and the technological capacity of different universities, promoting the link between industry and academia. The text box in Figure 2 shows an example of some general questions that are presented to the participants.

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Figure 2
Sample of general questions

1. What technological area best describes the project?
   a) Human-Machine Integration
   b) Manufacture
   c) Management of parts and/or tools
   d) Automatization
   e) Other area
2. How many people are currently working on the project?
   a) From 1 to 3
   b) From 4 to 7
   c) 8 or more
3. What is the scope of your project? Check all that apply
   a) Design
   b) Simulation
   c) Prototype manufacturing
   d) Continuous use of the designed product
4. How important is the use and analysis of data for project development?
   a) Insignificant
   b) Not very important
   c) Significant
   d) Crucial

3.2. Personnel

In these dimensions the aim was to measure the technical qualifications of the people that work in the project, understand efforts to help individuals acquire new skills, and identify collaboration or independent work, as it is not uncommon to work independently in academia. The description of each integration level can be found in Table 6, providing a general description of what can be expected in the environment surrounding the measured sub-dimensions, depending on the level of integration.

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Table 6
Personnel evaluation criteria

	Beginner	Intermediate	Experienced	Expert
1. Current qualifications	Little or no experience in digital technologies	Partial knowledge of some of the required digital technologies	Proficient in the required digital technologies	Possess senior-level knowledge
2. Collaboration	Meetings conducted in person; information exchanged via hard copies	Some meetings and data are exchanged digitally	Most meetings held via digital media; data stored digitally	All meetings and data are conducted or stored digitally

3.3. Manufacture and operation

This dimension places emphasis on the technical aspects of the projects, examining factors such as the extent to which machines collaborate with each other or interact with humans, the specific types of tools utilized in project assembly, their integration with I4.0 technologies, and the level of autonomy in operation (Table 7).

Table 7
Manufacturing and operation scoring criteria

	Beginner	Intermediate	Experienced	Expert
1. H – M or M – M integration	No integration between technologies	Systems are minimally integrated	Systems are partially integrated	Systems are fully integrated
2. Equipment	Equipment lacks I4.0 features and cannot be upgraded	Some equipment can be upgraded with I4.0 technologies	Most equipment hast I4.0 features or can be upgraded	All equipment operates under I4.0 principles
3. Parts or tools management	Tool do not operate autonomously, and parts are	Automatic tools or parts handling is in the testing phase	Autonomously guided tools or parts are only found in some processes	Autonomously guided tools or parts are present in all processes

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Table 7

Manufacturing and operation scoring criteria

	Beginner	Intermediate	Experienced	Expert
	handled manually			
4. Automatization	No automated processes exist	Few processes or machines are automated	Most processes are automated	All processes can be fully controlled through automation

3.4. Functionality based on collected data

This dimension evaluates the degree to which project functionalities are digitally modeled, examining the capacity for control through information technologies or algorithms. It also considers the system's ability to issue real-time alerts regarding its measured states and its capability to self-diagnose, thereby identifying and communicating issues to operators for resolution (Table 8).

Table 8

Data based functions measurement scale

	Beginner	Intermediate	Experienced	Expert
1. Decentralized	Stored data is not utilized	Collected data is used in some control processes	Data is used for process control and optimization	Data is extensively utilized for process control, optimization, and decision making
2. Interoperable	Collected data is not exchanged between devices	Some devices can be controlled by ICTs using sensor data	Sensor data is used to control devices with M–M capabilities	Data collected fully utilized to control all devices, each possessing M–M capabilities
3. Real–time	Manual maintenance is performed based	Some devices issue alerts when problems arise,	Devices self-diagnose some components	Devices can perform self-diagnosis on every

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Table 8

Data based functions measurement scale

	Beginner	Intermediate	Experienced	Expert
	on a predetermined schedule	which are addressed manually		component, pinpointing the exact defective component
4. Virtualization	Simulations are not utilized	Simple simulations of certain design components are employed	Supervisory Control and Data Acquisition (SCADA) is utilized in some areas	SCADA is employed throughout the entire device, resulting in a comprehensive digital twin

4. Discussion

After receiving feedback and improving the evaluation instrument, the questionnaire was distributed to members of the "Researchers for Mexico" program (CIDE, 2020; El Colegio de Sonora, 2024), administered by the Mexican National Council of Humanities, Science, and Technology, comprising approximately 1000 researchers working in Mexican institutions. According to the program data, 27% are engaged in technology-related projects. At the time this article was sent, a total of 17 responses were received. One response was randomly selected to illustrate how the framework assesses Industry 4.0 readiness for a project developed in a research environment. While the participant answered all questions, they indicated that some evaluated technologies were not necessary to accomplish their project objectives. The maximum points considered for evaluation are calculated using the following formula:

Points Considered = Total Points – 4 × (No. of questions marked as “Not needed”)

Hence, for the selected response, four questions were marked as “Not needed” in the Personnel dimension (two for the Current qualifications sub-dimension and two for the Collaboration sub-dimension), and three questions in the Parts and Tools management sub-dimension were also marked as “Not Needed” in the Manufacture & Operation dimension. The scores assigned to this response, the calculation of considered points, and the level of integration awarded in accordance with the proposed framework are detailed in Tables 9, 10, and 11. From the initial section of the instrument, it was determined that the aim of the project is in the simulation stage, thus excluding

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the need for a prototype development. Additionally, the participant researcher emphasized the importance of data usage in optimization tasks for their project.

Table 9
Personnel scoring

Sub-dimension	Points obtained	Considered points	Score (as %)	Level of integration
1. Current qualifications	24	32 - 4×2 = 24	100%	Expert
2. Collaboration	24	32 - 4×2 = 24	100%	Expert

Table 10
Manufacturing and operation scoring criteria

Sub-dimension	Points obtained	Considered points	Score (as %)	Level of integration
1. H – M or M – M integration	16	16	100%	Expert
2. Equipment	16	16	100%	Expert
3. Parts or tools management	2	16 - 4×3 = 4	50%	Intermediate
4. Automatization	8	16	50%	Intermediate

Table 11
Data based functions scoring

Sub-dimension	Points obtained	Considered points	Score (as %)	Level of integration
1. Decentralized	12	12	100%	Expert
2. Interoperable	12	12	100%	Expert
3. Real–time	9	12	75%	Experienced
4. Virtualization	9	12	75%	Experienced

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Upon analyzing the scores acquired, it becomes apparent that the *Data-Driven Functions* dimension emerges as the most robust aspect, exhibiting considerable strength in its evaluation. Conversely, the *Manufacture* and *Operations* dimension, while not alarmingly deficient, registers comparatively lower scores. This observation resonates with the preliminary information retrieved from the questionnaire's general section, wherein it was stated that the project's trajectory does not extend to the manufacturing phase, emphasizing the paramount importance of data utilization within the project's framework. Furthermore, an evident need for fortification is discernible within the *Virtualization* sub-dimension, a necessity underscored by the participant's delineation of the project's ultimate developmental objective as focused primarily on the simulation stage. Thus, these insights underscore the imperative for targeted enhancements to optimize the project's readiness across all relevant dimensions.

5. Conclusions

The proposed evaluation framework offers a support tool for researchers overseeing technological projects, facilitating the identification of engineering areas requiring reinforcement and pinpointing personnel capabilities needed. Additionally, it functions as a roadmap, guiding project progression towards higher levels of maturity. While acknowledged as not providing a holistic assessment for academic projects, it was meticulously crafted to encompass technologies commonly encountered in research labs, thus serving as a versatile evaluation tool across a broad spectrum of projects.

Given its consideration of various technology areas (including manufacturing, automation, and integration) and its adaptable scope selection (encompassing design, simulation, prototype manufacturing, and continuous service provision), the framework does not prescribe definitive steps for achieving expert-level integration. Instead, it focuses on assessing the current technological landscape surrounding a project. However, as a prospective research direction, the framework could potentially evolve to offer strategic roadmaps tailored to specific technological areas and development goals, thereby facilitating the comprehensive integration of Industry 4.0 principles.

Upon the conclusion of the questionnaire response period, valuable insights can be retrieved, providing a comprehensive overview of characteristics specific (at the current research state) to Mexican public research centers and universities. This includes insights into the general technological capacity for industrial projects and areas requiring strengthening across various institutions. Such information serves as a valuable resource for visualizing the technological landscape and identifying areas for improvement within the academic sector.

In addition to the points mentioned, it could be beneficial to emphasize the potential impact of the proposed evaluation framework beyond individual projects. This could involve discussing its broader implications for fostering

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collaboration and knowledge-sharing within the academic community, ultimately contributing to the advancement of Industry 4.0 initiatives on a national scale. Additionally, highlighting the importance of ongoing refinement and adaptation of the framework based on feedback and emerging trends could underscore its relevance and effectiveness as a dynamic tool for continuous improvement in technological research and development.

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Media

The survey (in Spanish) can be found on: https://forms.gle/9KhWHCxnqkKJQQs37

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