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Review

A Review of Industry 4.0 Assessment Instruments for Digital Transformation

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Featured Application: A robust Systematic Literature Review (SLR) of assessment instruments (maturity models, roadmaps, frameworks, and readiness assessments) to assess the level at which Industry 4.0 is deployed in an organization. The research provides a comprehensive perspective of readiness assessment instruments for Industry 4.0 digital transformation and sets the foundations for future action plans and projects.

Abstract: Nowadays, different Industry 4.0 technologies have been implemented into diverse industries. However, these implementations are not standardized across similar industries and countries. Consequently, companies are actively looking for assessment instruments—maturity models, roadmaps, frameworks, readiness assessments—to assist in their digital transformation, to determine their Industry 4.0 level, and to identify technologies and strategies that should be implemented in specific areas, thus developing a feasible implementation plan. A review is conducted following the PRISMA (Preferred Reporting Items for Systematic Literature Reviews and Meta-Analyses) methodology to analyze the different research works on assessment instruments focused on Industry 4.0. A total of 538 articles, book chapters, conference proceedings, editorial material, reviews, and reports written in the English language were retrieved. Of these, 132 research papers were examined using a mixed analysis format to generate bibliometrics, and 36 articles were then deeply studied for a complete meta-analysis. The findings and insights of this meta-analysis led to a compilation and summary of dimensions, outcomes, enablers, and key components typically involved in Industry 4.0, which are comprehensively integrated to present the best practices for assessing Industry 4.0 and deploying a digital transformation that can impact productivity, flexibility, sustainability, quality, costs, and time.

Keywords: Industry 4.0; digital transformation; assessment instruments; readiness assessment; maturity models; smart factory; framework; roadmap; Systematic Literature Review

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1. Introduction

The concept of Industry 4.0 arose in the light of information technology, including digitalization, virtualization, and faster response time (Hamilton et al., 2020) [1,2]. Industry 4.0 has experienced rapid growth due to the high demand for mass personalized products and the accessibility of hardware and software solutions, such as networking equipment, cloud computing, and big data analytics [3]. Industry 4.0 involves a digital transformation focusing on improving operational efficiency, developing better customer relationships, and customizing sustainable products. The products and solutions derived from the organizational implementation of Industry 4.0 are based on intelligent information systems that obtain, handle, and analyze data to help companies identify their current capacity to expand their business activities [4,5].

Industry 4.0 incorporates innovative organizational and technological capabilities that allow companies to develop new internationalization strategies, giving them a competitive advantage that fosters their growth and positioning worldwide.

Digital transformation includes technology, the company's employees, business models, processes, and organizational structures [6]. Also, digital transformation impacts all sectors within an organization and shapes the industry's future, including processes, working conditions, and specifications [5].

However, developing and implementing digitalization initiatives faces different environmental barriers and challenges, particularly the need for more technical, individual, and organizational skills [7]. Moreover, legacy equipment imposes additional challenges since outdated devices and systems often lack modern authentication, encryption, and security monitoring capabilities making them vulnerable to attacks that can affect the assets and processes [8]. Hence, businesses are overwhelmed by the current industrial progression while struggling to develop appropriate implementation plans for multidisciplinary Industry 4.0 initiatives [9,10].

This problem derives from a shortage of strategic guidance, poor understanding of Industry 4.0, uncertainty about the project outcomes, failure to properly assess the internal capabilities to implement Industry 4.0, complex processes, and high-risk investments. Also, companies require an extensive perspective on their strategy, organization, and operations to be able to understand where they stand and the level of preparedness, which is commonly called "maturity level" [11].

Thus, there is a need for tools and models to both evaluate the level at which the technologies are currently used and apply the Industry 4.0 foundations based on the needs of the organization [9]. According to Gollhardt et al. [12], some digital transformation models do not have solid theoretical bases or structures, since many are just empirical studies. Another issue is that many maturity models regarding Industry 4.0 focus on technological aspects and fail to include more comprehensive dimensions, e.g., culture and leadership, which contribute to the strategic components like workforce skills and new product and service development [13,14].

Due to the new market demands and technology usage increase, Industry 4.0 maturity models must be updated [15]. Hence, it is essential to create instruments and methods that (1) identify the organizational and technological needs, (2) assess the maturity toward digital transformation, and (3) support organizations in the transformation process.

When implementing Industry 4.0, organizations commonly deal with the absence of strategic tools, lack of managerial and organizational support, misunderstanding of Industry 4.0 notion, and unknown results and benefits of conducting Industry 4.0 projects. Also, the financial factors are considered a barrier to Industry 4.0 performance. Additionally, organizations are still determining the transformation's investment costs and possible outcomes [11,16].

Notwithstanding the roadblocks, research contributions in numerous interdisciplinary areas where digitization and sustainability perspectives are present have helped the evolution of industries through time. Industry 4.0 is a shared framework for faster development where all these contributions come together to build the manufacturing system for the factories of the future.

It is vital, then, to carry out the transformation with a clear path and Industry 4.0 deployment guidance. Some companies are actively looking for instruments (maturity models, frameworks, roadmaps, and readiness assessments) to assess their current state (maturity level) and support digital transformation. Also, companies need to both identify the technologies or strategies that should be implemented and develop an appropriate investment plan.

This study diverges from the conventional use of the Technology Readiness Level (TRL) in evaluating technology maturity within new product development or innovation research [17]. Rather, it concentrates on tools that evaluate management implementation capabilities, like the well-regarded RAMI 4.0, which is a comprehensive framework of standards, practices, and references intended for the development of Industry 4.0 readiness assessment methods [18].

This research paper aims to analyze the assessment instruments available in the literature and identify the key Industry 4.0 components and models through a Systematic Literature Review (SLR) following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology. The goal is to build a robust assessment instrument, considering the main contributions found in the key papers.

Therefore, the specific objectives of this research are (i) to synthesize the main findings of the literature by including the most relevant elements for the research; (ii) to perform an SLR following the PRISMA methodology to meet previous models, frameworks, roadmaps, questionnaires, or other instruments developed over the years; and (iii) to provide theoretical guidelines to elaborate a comprehensive assessment instrument for Industry 4.0.

The remainder of this paper is organized as follows. Section 2, defines the PRISMA methodology used to conduct this study. Section 3 presents the main findings of the study. We discuss the different implications identified in terms of assessment instruments for Industry 4.0 in Section 4. Finally, Section 5 presents the conclusions, limitations, and agenda for further research.

2. Methodology

PRISMA facilitates transparent and complete reporting in the current research work, providing the key papers on the research field and efficiently confronting much information [19]. The authors followed this rigorous method (PRISMA 2020) to identify the most relevant components in the literature regarding tools or instruments to assess the Industry 4.0 maturity level and the current digital transformation.

The Research Questions (RQs) that inspire this research are:

RQ1: What resources are available in the literature for assessing Industry 4.0, (e.g., instruments, frameworks, maturity models, and roadmaps) and what insights can be gained from them?

RQ2: What are the essential components that need to be included in an assessment tool for digital transformation in the context of Industry 4.0?

The steps and phases of PRISMA systematic methodology are presented below.

2.1. Eligibility Criteria

In reviewing instruments and tools for digital transformation and Industry 4.0, the eligibility criteria considered various elements such as keywords, titles, abstract, language, content type, year, subject area, and publication title.

- Keywords, titles, and abstract: The main words used in the eligibility criteria for keywords, titles, and abstract were questionnaire, roadmap, maturity model, framework, digital transformation, and Industry 4.0.
- Language: The language considered was English.
- Content type: All content types were considered. Some of these were articles, conference papers, review articles, and book chapters, among others.
- Year: All years up to mid-December 2023.
- Subject area: All subject areas were included.
- Publication title: All publication titles were included.

2.2. Information Sources

Web of Science (WoS), SCOPUS, and Emerald are the three databases used for the PRISMA methodology data collection. These databases were selected because of their engineering inclination. They have a vast collection of papers. In addition, Google Scholar was used to complement the search.

2.3. Search Strategy

The search strategy process first performs the motor search, which varied from iteration and for each database. The keywords used for all query iterations were "*questionnaire*", "*maturity model*", "*framework*", "*roadmap*", "*digital transformation*", "*Industry 4.0*", "*assessment tool*", "*survey*", "*form*", "*evaluation*", "*evaluation level*", "*assessment level*", "*assessment*", "*digitization*", "*digitalization*", "*maturity readiness*", and "*readiness level*". All words were considered in all fields, such as titles, abstracts, and keywords. A filter is applied to language to only English, and no search criteria are applied to years.

2.4. Selection Process

The selection of articles is carried out after including all papers in an Excel spreadsheet and eliminating duplicates. The selection process is based on a conditional process that eliminates articles if they do not have a specific combination of keywords. Two combinations of keywords were considered. The first consists of: *"Questionnaire" OR "Survey"*, *"Roadmap" OR "Maturity Model" OR "Framework"*, *"Digital" OR "Digitalization"*, *"Assessment" OR "Readiness"*. Meanwhile, the other combination is: *"Questionnaire" OR "Roadmap" OR "Maturity Model"*, *"Digital" OR "Industry 4.0"*, *"Assessment" OR "Evaluation."* These words are chosen given that this research aims to scope articles with Industry 4.0 and digital transformation instruments. Abstracts are filtered based on the existence of certain combinations of keywords.

2.5. Data Items

The findings of the data items were divided into seven sections:

- Definitions: Concepts such as maturity model, roadmap, framework, and readiness assessment are defined because some papers are not clear about what they are proposing, which makes it confusing for the reader to understand the outcome.
- Type of research: The types of papers are divided into these sections: article, book chapter, conference proceedings, editorial material, review, and report. A brief analysis of these papers is conducted about the number of papers each section has and the topics being covered.
- Findings per year: All years to present were considered when searching in the databases. However, publication records for this topic (considering the eligibility criteria) started in 2017. Consequently, only papers from 2017 to 2023 were identified. The year 2022 is the year when most publications regarding the concepts studied are published.
- Publisher: 38 different publishers are mentioned due to the systematic review process. Section 3.4 shows the most relevant publishers.
- Country: Papers are being published all around the world. However, Europe is the continent with the most publications, with Germany being the country most relevant.
- Case studies: Some of the papers included a case study. These papers were analyzed by the title, author, industry where the case study was applied, assessment instrument, and a brief description of the tool and application. Most of these studies were applied in the automotive and manufacturing industries.
- Frequent keywords: The most frequently used keywords are analyzed to determine the most used for new proposals in the assessment instrument for Industry 4.0 and digital transformation. Digital, industry, maturity, and model were the most popular keywords.

2.6. Study Risk of Bias Assessment

The assessment of bias helps to determine the transparency of evidence synthesis results and findings [20]. For this SLR, the CASP Systematic Review Checklist was followed to reduce the risk of bias and was followed also to report the bias assessment [21].

2.7. Effect Measures

This does not apply to this research given that an SLR is conducted rather than an experiment. No method was used due to the type of data obtained (qualitative). In addition, there are no statistical or experimental data.

2.8. Synthesis Methods

The papers included in the study were thoroughly read. Articles are selected if they comply with the eligibility criteria, which are based on the research questions and the following considerations:

- The manuscript proposes a tool (maturity model, framework, roadmap, survey, questionnaire, form, assessment tool, evaluation, instrument) for Industry 4.0 and digital transformation.
- Application of technology, enablers, and drivers for the proposal.
- Some sort of validation method is included.
- The article is written in the English language.

After this process, a comparative data-based analysis shown in Section 3.8, created for the selected papers to identify the most important findings. This analysis consists of a table that includes relevant characteristics that help describe each selected paper: outcome, inclusion of an additional instrument/model, methodology, validation method, drivers, dimensions, industry, objective, and contribution.

2.9. Study Selection

As previously mentioned, the search strategy started with three databases and one search engine (WoS, SCOPUS, Emerald, and Google Scholar). The search provided a total of 536 papers. After screening and eliminating duplicates, 368 papers were left.

Therefore, 238 papers were excluded after reviewing if specific keywords appeared in the abstract. These keywords were mentioned previously in Section 2.4. Afterward, a total of 132 papers were considered for developing the scoping review presented in Section 3. These papers were analyzed by their title abstract, figures, and conclusions.

Consequently, for the study selection, 36 papers were included for further analysis and the final review. In Figure 1, the flow diagram of the study selection is presented.

2.10. Study Characteristics

Four terms were identified as attributes and described as a *maturity model*, *roadmap*, *framework*, *and readiness assessment* based on the first eligibility criteria. Subsequently, papers are categorized based on their type and the year of publication. This procedure aids in determining if the paper's subject has been pertinent to the body of literature over time.

Publishers are also analyzed to identify the existence of Industry 4.0 and digital transformation across many industries. Additionally, articles are categorized based on the nation and continent in which they were published. For the 132 publications, the following features were determined: definitions, document type, year, publisher, country and continent, case studies, and frequently occurring keywords.

Finally, case studies are identified in these papers and the most frequently used keywords. For the 36 papers included in the final review, other types of variables were analyzed: the kind of outcome (assessment instrument), the inclusion of other tools, methodologies, validation methods, drivers, dimensions, industries, objectives, and contributions. These variables help identify the relevant findings for improving the assessment instrument. The findings will be described in the following Section 3.

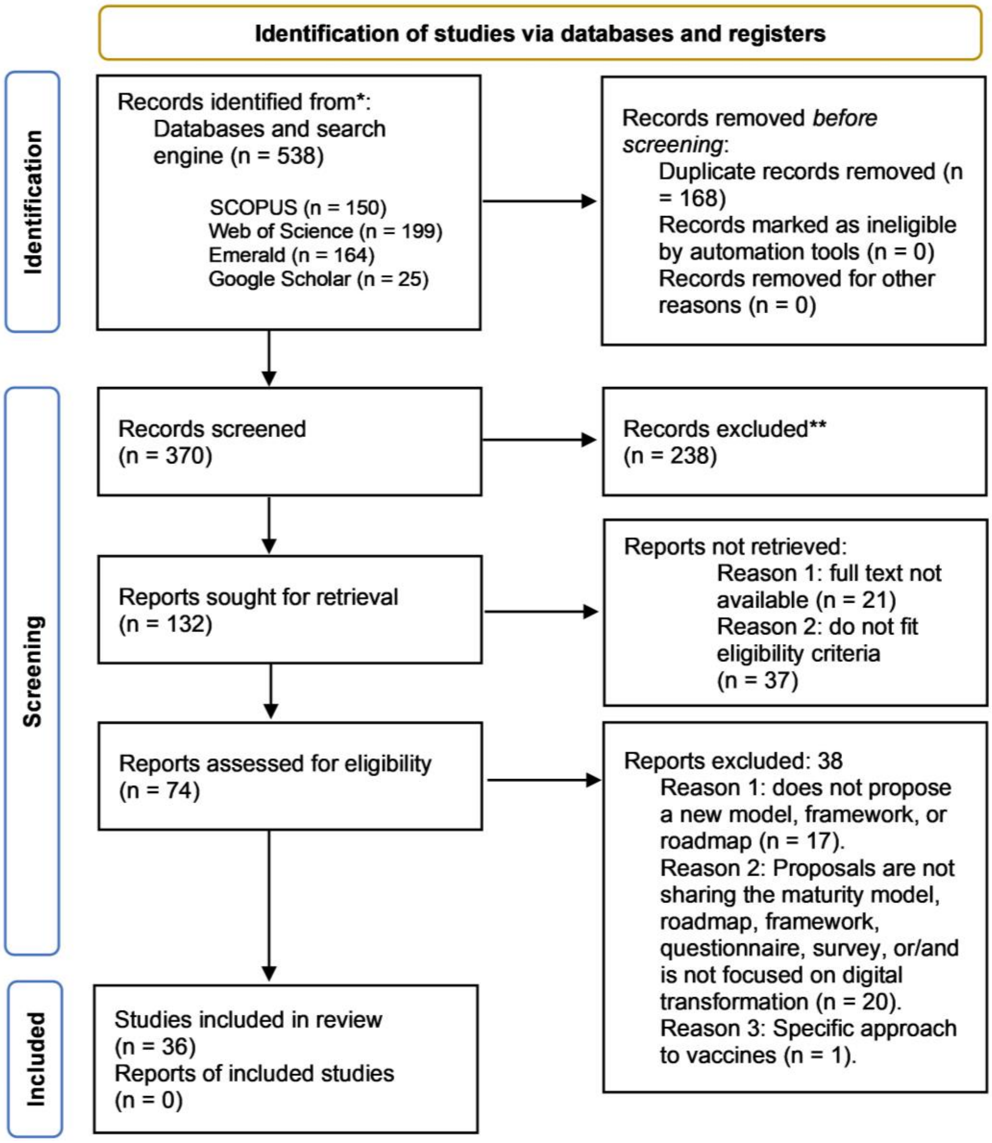

Figure 1. SLR Flow diagram—study selection. * Described on Sections 2.1–2.3, ** Described on Section 2.4.

3. Results

The results and findings from the SLR are conducted in this section to understand the context of Industry 4.0 and gaps and future trends. Additionally, a deep meta-analysis is conducted to identify those characteristics of existing instruments to assess digital transformation and Industry 4.0.

Section 3.1 presents the different definitions, and Section 3.2 shows the findings from the 132 articles.

3.1. Definitions

Most articles interchange concepts amid maturity models, roadmaps, frameworks, and readiness assessments, which may confuse practitioners and researchers. Since there is a need to have a clear construct of what these concepts imply, a proposed definition of them is presented below.

- Maturity models are instruments that provide knowledge about the organization's current capabilities to execute a particular task and the level of progress toward an objective. These models offer comprehensive guidance that supports an improvement in certain tasks—in this case, the implementation of Industry 4.0. These usually include qualitative dimensions and levels of progress that allow assessing the company through a **set of guiding questions** [11,12,14,22,23].

- A roadmap is a comprehensive plan that includes dimensions and drivers for digital transformation in an organized approach. It provides a look into the future of a particular area; it is a **knowledge tool** for businesses [24]. It provides orientation for decision making and helps foresee future technologies and strategies for obtaining a competitive advantage. For Industry 4.0, organizations can develop a roadmap to improve the implementation process and increase their maturity level [24]. Also, **a roadmap includes a set of recommendations** for guiding companies, in this case, for digital transformation [10].
- A framework provides a **foundation for developing instruments and methodologies**; it is a holistic approach that can help adopt digitalization [25]. Also, a framework may provide structure to the research. Additionally, according to Pirola et al. [22], they enable benchmarking and performance improvement.
- A readiness assessment is a systemic analysis of an organization's ability to cope with and undertake a transformational process or change. Also, it is a **measure and evaluation process** to identify implementation facilitators and barriers, opportunities and potential challenges or risks. Thus, it provides an opportunity to address any gaps in the existing organization [26]. The main objective is to reduce the transformation process implementation failures effectively [27]. For that, it must effectively identify (a) the high-performance strategies for frontline responders [28]; (b) tools that are needed for the company's core engagement, technological transformation, or skills [27]; and (c) the relationship between the actors and variables in the system; for instance: customer resources, operation/service processes, quality, among others [29].
- For this study, the authors proposed the following construct for an **assessment instrument**: englobes any of the previously defined instruments maturity model, roadmap, framework, readiness assessment as well as other tools identified in the SLR such as questionnaires, checklists, surveys, diagnostic tools, or leveling instruments. Each one of the assessment instruments defined aims for the continuous improvement of a system from a holistic or micro-point of view. It considers the variables, actors, stakeholders, processes, and worldview of the system in the context to which it belongs and impacts.
- *Industry 4.0* is based on merging the cyber and physical dimensions, combining the physical and digital realms, fostering the integration of advanced technologies, such as augmented reality, automated manufacturing, Internet of Things, cloud computing, artificial intelligence (AI) and machine learning (ML), (industrial) big data, big data analytics, fog and edge computing, robotics, cybersecurity, semantic web technologies, and additive manufacturing [30].

Since the literature is ambiguous about the definitions of these concepts, it is relevant to provide a definition, identify the type of instruments and models that are available in the literature, and determine what kind of instrument is being developed in this research.

3.2. Bibliometric Analysis and Findings

This section presents a bibliometric meta-analysis of 132 research articles following the methodology described in Section 3. Visualizing bibliometrics reveals publication trends, top contributing authors, countries with the highest productivity, and most contributing journals in the field.

Type of Research

The studies scoped are based on concepts such as Industry 4.0, digital transformation, and assessment tools/instruments. Figure 2 shows the distribution of documents identified for the scoping review. Also, instruments for digital transformation and Industry 4.0 assessments are usually being developed as maturity models, roadmaps, frameworks, and readiness assessments. Additionally, the proposed instruments found in the literature follow qualitative (case studies, conceptual frameworks) and quantitative methodologies (surveys).

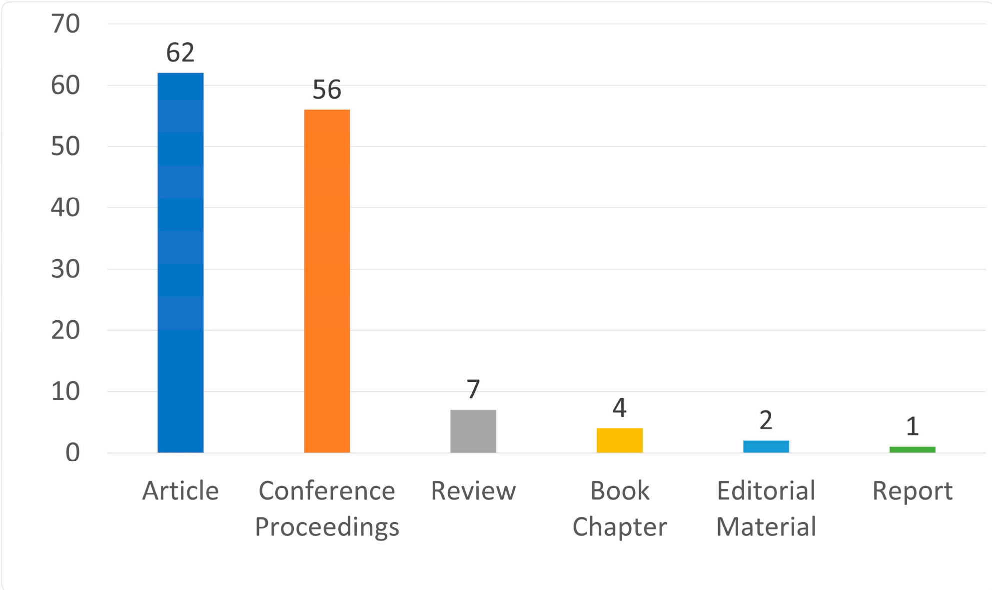

Figure 2. Distribution of type of research scoped.

3.3. Findings per Year

The number of documents in the literature has increased throughout the years as the concept of digital transformation gains relevance. Figure 3 presents the growth in published papers throughout the years. The scoping review included all papers to date, but the oldest is from 2017. The last search was conducted in early 2023. All papers from 2017 focus on the manufacturing industry; however, one study conducted by Agca et al. [31] delivered a report where a broad range of sectors was considered, such as automotive, electronics, engineering, construction, food and beverages, and aerospace, among others. As the years pass, the industry's focus is expanding to other areas, including oil and gas, bank treasury, healthcare, apparel, sustainability, and more. The number of documents published per year regarding these topics is expected to grow and evolve in the following years.

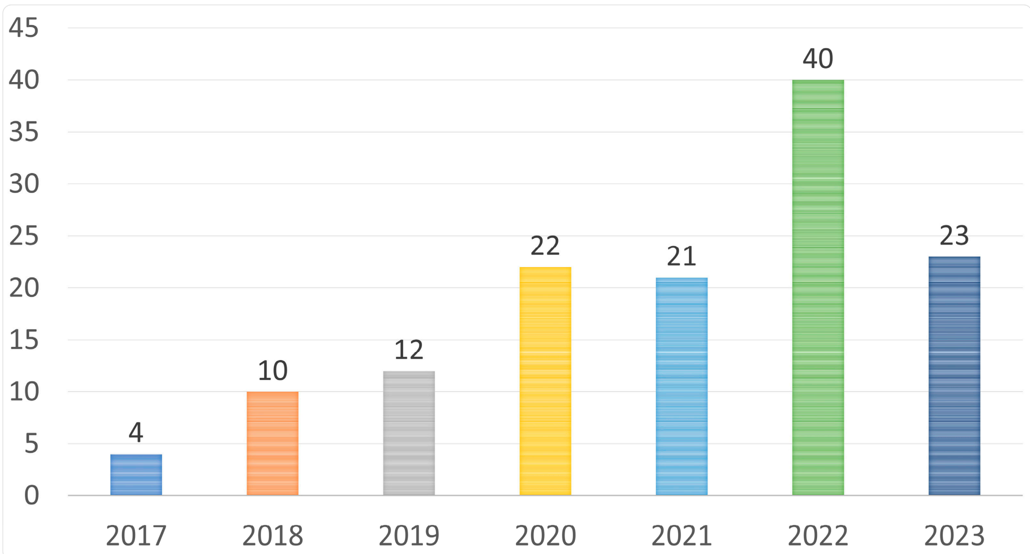

Figure 3. Number of papers published per year.

3.4. Publisher

Figure 4 presents the consolidated publishers that were found in the literature review. The purpose of having a publisher rather than the traditional journal view was to avoid any biases that may direct authors to select specific journals when looking for options to publish an article. Using a publisher view also shows if the interests of research in certain fields are widespread among different academic ideologies or regions associated with each publisher. Springer is the publisher with the most articles regarding assessment instruments for digital transformation and Industry 4.0. The instruments included by this publisher include maturity models, frameworks, roadmaps, and readiness assessments.

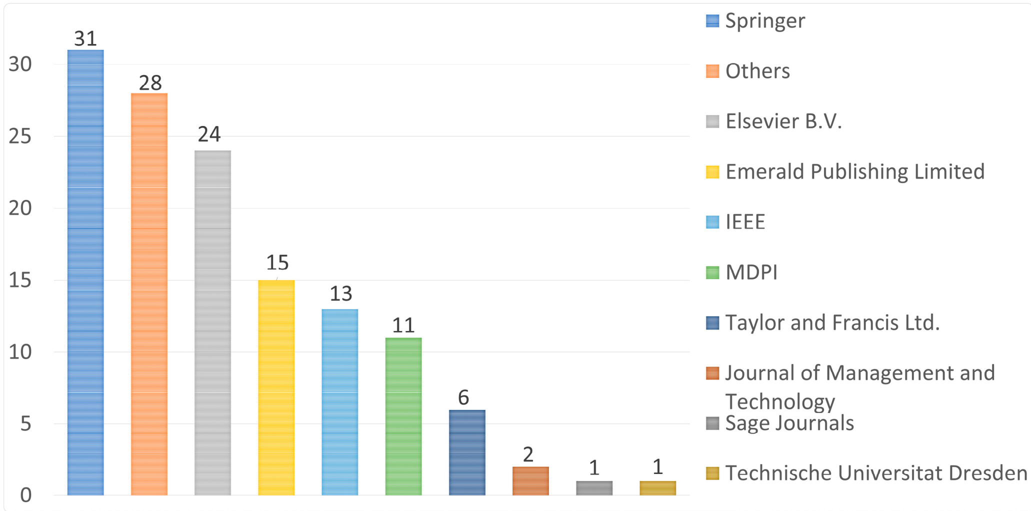

Figure 4. Number of papers per publisher.

These tools are developed for large, medium, and small enterprises. Also, Springer includes tools for different sectors like industrial engineering, business process management, and automation, among others. It can be considered that the other relevant publishers are Elsevier and Emerald Publishing Limited; besides the number of articles that they published, they are the publishers that usually publish maturity models, frameworks, roadmaps, and readiness assessments.

3.5. Country

Figure 5 shows how the contributions to the literature are distributed around the countries. While countries with the most papers are in green, countries with the least contributions are in red. The countries in white mean that there are no papers found regarding digital transformation, assessment tools, or Industry 4.0 in the databases when the eligibility criteria were applied.

It is observed that the country with the highest number of articles is Germany. Given that Industry 4.0 arose in this country, they may hold an advantage in the development of a digital transformation assessment model. Switzerland, Italy, and Turkey are the following countries with the most literature, with nine, eight, and eight papers, respectively. Switzerland particularly presents articles that provide a foundation and methodologies for developing tools to help implement digital transformation and Industry 4.0. On the other hand, those studies from Italy focus on trending topics in evaluating Industry 4.0 and industries like manufacturing companies and healthcare. Additionally, research studies conducted in Turkey used quantitative methods and validation approaches such as Spherical Fuzzy COPRAS, Analytic Hierarchy Process, and intra-class correlation, among others. Nonetheless, Germany is at a more advanced level in terms of technology, and their assessment approaches seem to be more comprehensive or robust.

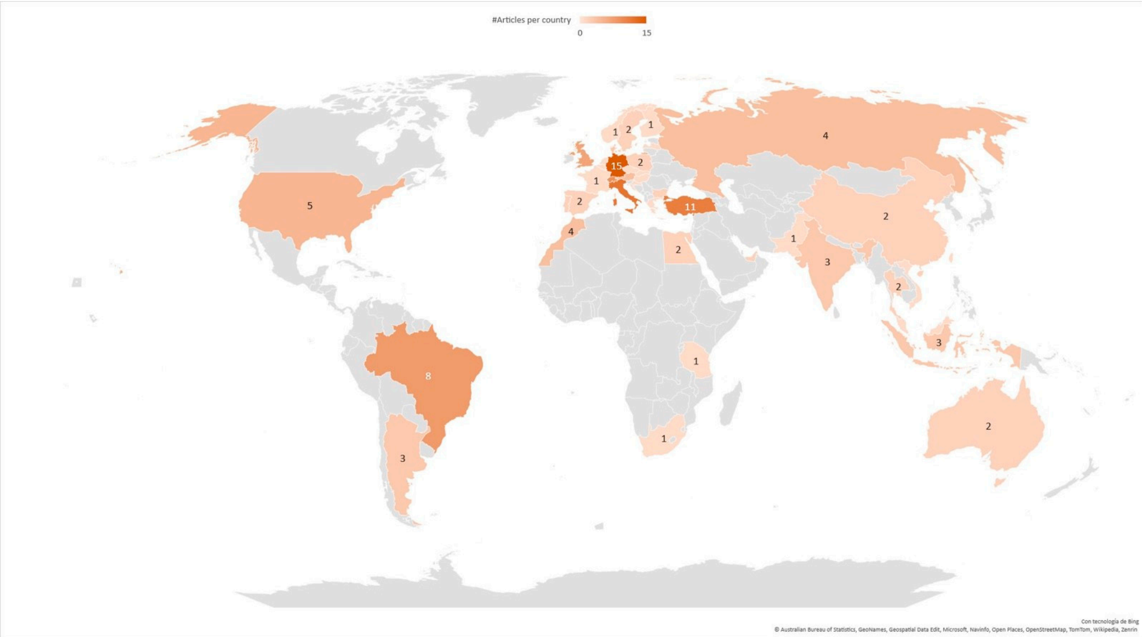

Figure 5. Distribution of literature per country.

3.6. Case Studies

The literature that includes case studies provides insight into the context and perspective of the proposed outcome. It also helps understand the relationship between the theory and practical implications. Therefore, it is important to highlight the studies that present a case study.

Supplementary Materials shows the SLR analysis and information for the 16 articles that use case studies as a validation method. The table includes the paper's title, author, industry where the case study was developed, assessment instrument used, and a description of the tool and case study. Most case studies were carried out in manufacturing industries.

The case studies are applied in countries like Thailand, Portugal, Turkey, Taiwan, and China. These articles help broaden the overview of the available literature and identify current assessment instruments for Industry 4.0 as well as trends and applications.

As summary findings of these studies, (i) some papers considered several dimensions to evaluate the company level of digital transformation; (ii) several of these dimensions are manufacturing and operations, strategy and organization, smart factory, technology, social, and environmental; (iii) some of the papers present different proposals as maturity models, roadmaps, frameworks, and readiness assessments, which provide a broad perspective on how both the implementation and evaluation of Industry 4.0 can be tackled; (iv) various authors based their focus on small and medium enterprises [32,33].

3.7. Frequent Keywords

A word cloud is generated to represent the frequent keywords used in papers. These frequent keywords are important since they provide information about possible dimensions, drivers, and important characteristics of digital transformation and Industry 4.0 implementation.

A smaller list was created from all keywords to show the most recurring ones. Figure 6 represents the most frequently used keywords in the papers. The most important words are in bigger font sizes and a deeper blue color, such as digital, industry, maturity, and model.

It is also important to identify the smaller font keywords, since they may give context about Industry 4.0 elements that may not be considered at first hand but are still relevant, such as management, transformation, assessment, technology, and strategy. Strategy, management, and technology may give insight into the implications of Industry 4.0 and digital concepts and their relationship.

Figure 6. Most frequent keywords.

These words may help with the search for papers that include important assessment outcomes and other relevant information and provide directions for the next steps of the research. For instance, consider the last keywords, which are defined as manufacturing, smart SMES, process quality, roadmap science, data design, and business capability.

The results presented in this section provided significant insights to set up the meta-analysis and respond to the RQs. The following Section 3.8, will show the analysis of the key papers of this study.

3.8. Analysis and Findings of the Key Research Studies

The SLR led to 36 studies obtained through the PRISMA methodology. Table 1 presents the abbreviations used in Table 2. The articles and authors' names are shown in Supplementary Materials. Characteristics of the literature are summarized in Table 2. The meta-analysis includes elements such as the proposed instrument and any additional tool developed besides the main proposal, methodology, validation method, drivers, dimensions, industry, objective, and contribution.

Table 1. Abbreviations used for Table 2.

Concept	Abbreviation
Big Data	BD
Cloud Computing	CC
Cyber–Physical Systems	CPS
Sustainable Development Goals	SDGs
Industry 4.0	I4.0
Small and Medium-Sized Enterprises	SMEs
Internet of Things	IoT
Key Performance Indicators	KPIs
Case Study	CS
Literature Review	LR
Circular Economy	CE
Information Technology	IT
Business Process Management	BPM
Digital Transformation	DT
Not Available	NA
Digital Governance Assessment Framework	DGRA
Additive Manufacturing	AM
Augmented Reality	AR
Artificial Intelligence	AI
Automated Guided Vehicles	AGV
Human–Machine Interface	HMI
Radio-Frequency Identification	RFID
Real-Time Location Systems	RTLS

Table 2. Synthesis of the Systematic Literature Review.

# Paper (See Supplementary Materials)	Outcome	Assessment Tool Included in the Article	Methodology	Validation Method	Drivers	Dimensions	Industry	Objective	Contribution
1	Framework	No	Qualitative and quantitative	LR, CS, Delphi method	Information and communication technology infrastructure, CPS, smart factory, SDGs, horizontal and vertical integration, leadership, employee willingness.	Economic, environmental, social, policy, process, product, strategy, technology.	Smart circular supply chain.	Evaluate the readiness and maturity level for I4.0 and CE in SMEs.	Readiness and maturity model that combines I4.0 and CE in a smart circular supply **chain** context.
2	Roadmap	Questionnaire	Qualitative and quantitative	LR, CS	CPS, embedded systems, horizontal and vertical integration, sensors, employee willingness.	Technology, products, customers and partners, value creation processes, data and information, corporate standards, employees, strategy, and leadership.	Manufacturing.	Present a new I4.0 guidance model.	Develop an integrated approach to lead from the first contact in I4.0 until the specific timelines, resources, and responsibilities are defined for the company.
3	Readiness assessment	Questionnaire and regression model	Qualitative and quantitative	CS	General technological drivers.	Strategy, organization, user interaction, partnership, operating activities, technology, innovation.	IT department.	Develop a model that quantifies the readiness of an IT department for its digital business transformation.	Better decision making when entering the digital market, comprehension of digital bottlenecks, better at identifying problems, increased competitive strategies, improved digital products and services.
4	Framework	No	Qualitative and quantitative	LR, CS	Willingness to change, innovation management, equipment infrastructure, leadership, KPIs, coordination.	Technology, production processes, people, product, change, organization.	Manufacturing in SMEs.	To propose a framework for a maturity model to assess the I4.0 maturity level of SMEs.	Help SMEs and companies with low maturity levels obtain the benefits of I4.0, evaluate their own maturity and help analyze their current strategies.

Table 2. *Cont.*

# Paper (See Supplementary Materials)	Outcome	Assessment Tool Included in the Article	Methodology	Validation Method	Drivers	Dimensions	Industry	Objective	Contribution
5	Framework	No	Conceptual	LR	Principles of process execution, modeling, design and improvement, IT tools, requirements for people working.	Asset management, data governance, application management, process transformation, organizational alignment.	BPM.	To develop a theoretical framework of the BPM maturity assessment process that includes the BPM implementation and one the includes the DT requirements.	Enables companies to perform a more reliable assessment of process maturity than current BPM maturity models.
6	Readiness assessment	Questionnaire	Qualitative and quantitative	CS	NA	Leadership and governance, user-centered design, public administration and change management, capabilities, culture and skills, technology infrastructure, data infrastructure, strategies and governance, cybersecurity, privacy and resilience, legislation and regulation and digital ecosystem.	Land services.	To develop an assessment tool for evaluating DT of land services in Indonesia based on the World Bank´s DGRA model.	Ensures that land services can be implemented digitally and helps develop a strategy for the progression of the land service business process.
7	Maturity model	No	Empirical	LR, CS	CC, Web 2.0, digitally rooted corporate culture and interoperability.	Customer, logistics, suppliers, integration, production, planning and control, quality and maintenance	Operations and supply chain management in manufacturing.	To develop a I4.0 maturity model for operations and supply chain management based on an existing procedure model	Assess the operations and supply chain management digitalization in real-life conditions and provide organizations measurable results.

Table 2. *Cont.*

# Paper (See Supplementary Materials)	Outcome	Assessment Tool Included in the Article	Methodology	Validation Method	Drivers	Dimensions	Industry	Objective	Contribution
8	Framework	No	Qualitative and quantitative	LR, CS	Quality management principles, leadership, organizational culture, processes management, BD, smart sensors, IoT.	Strategic direction, people and culture, processes and methods and tools.	Quality management	Propose a framework and methodology that assesses and measures the maturity level for Quality 4.0.	Incorporates new technologies with traditional practices and optimize them for better performance and innovation.
9	Framework	No	Qualitative	LR, CS	Customer focus, fact-based decision making, employee involvement, process management, integrated systems, leadership commitment.	People and culture, I4.0 awareness, organizational strategy, value chain and processes, smart manufacturing technology, product and service-oriented technology, I4.0 base technology.	Quality management in automotive component industry.	To develop a Quality 4.0 framework and present its application in an automotive company during the DT.	Contributes with the growing amount of I4.0 and DT literature in the context of operations management and helps understand how to work toward the transformation of quality management processes.
10	Assessment tool	No	Qualitative	LR	Industrial IoT, BD, CC, AM, simulation, CPS, autonomous robots, KPIs.	Foundation, product design, production planning, production engineering, production execution, services, infrastructure.	Manufacturing in SMEs.	Define the I4.0 priorities for Indian small and medium discrete manufacturing establishments through a questionnaire assessment survey.	Guide organizations define their digital strategies and help plan and execute them efficiently.
11	Framework	Questionnaire	Qualitative and quantitative	LR, CS	Digital skills, technology adoption, digital strategy, data analytics, technology infrastructure, front office, back office.	People, technology, process, customer and strategy, and investment.	General.	Develop a framework for assessing the level of DT of an organization.	Provides a quantitative approach for digital readiness at the organizational level. Helps the understanding and evaluation of the DT of museums.

Table 2. *Cont.*

# Paper (See Supplementary Materials)	Outcome	Assessment Tool Included in the Article	Methodology	Validation Method	Drivers	Dimensions	Industry	Objective	Contribution
12	Assessment tool	No	Qualitative	CS	Assign clear responsibilities, collaborative organizational structure, digital skills, data flow integration, IT infrastructure.	Digital strategy, digital maturity models, digitalization, investments, data analysis and KPIs.	Manufacturing.	Identify and organize the circumstances of the readiness for DT through a questionnaire.	Understand how change processes management applies to DT.
13	Framework	No	Qualitative and quantitative	LR, CS	Investment planning, project management, horizontal and vertical integration, data analytics, IT cybersecurity.	Strategy and governance, organization and corporate culture, smartness, employees, processes, customer.	Manufacturing.	Propose a new maturity model development framework based on design theory and develops a DT maturity model using this framework.	Provides guidance to develop a maturity model regardless of the domain, extends the design science literature and demonstrates the applicability of the framework.
14	Maturity model	No	Qualitative	LR	CC, IoT, IT security, data analytics, BD tools, data flow, integration of manufacturing and automation technologies, IT personnel skill set and planning, acquisition, production and sale, and distribution.	Asset management, data governance, application management, process transformation, organizational alignment.	Manufacturing.	Propose a maturity model for I4.0 based on software process improvement and capability determination.	Standardize development, provide higher quality, more flexibility, continuous benchmarking, global competition, job creation.

Table 2. *Cont.*

# Paper (See Supplementary Materials)	Outcome	Assessment Tool Included in the Article	Methodology	Validation Method	Drivers	Dimensions	Industry	Objective	Contribution
15	Readiness assessment	Questionnaire	Triangulation	LR, CS	AR, AI, blockchain, cloud storage, coordination, collaboration.	Organizational, technological.	Healthcare.	Examine the technological and operational capabilities that impact the level of organizational e-readiness for DT in Polish primary healthcare providers. Develop a model for DT organizational e-readiness.	Provide guidance for healthcare staff when developing strategies and distributing medical resources. Help healthcare staff of primary healthcare providers assess the e-readiness for DT and overcome barriers.
16	Maturity model	No	Qualitative and quantitative	LR, CS	Organizational structure, horizontal and vertical integration, CC, digital cost, strategy design, efficiency measure, intelligent cost construction capability.	Top-level design, infrastructure, cost consultation business process, professional management, comprehensive integration and digital cost performance.	Cost consultation.	Develop a digital maturity model to evaluate the digital maturity level of cost consultation enterprises.	Measures the digital level of cost consultation from multiple dimensions. Provides a guiding tool for DT of cost consultation. Provides a theoretical reference for DT of the cost consultation industry.
17	Roadmap	Quantitative scorecard	Empirical, quantitative	LR	AI, machine learning, BD analytics, CC, robotic process automation, distributed ledger technology, natural language processing, and application program interface.	Digital leadership, technical knowledge, data and insights, technology infrastructure, automation of process.	Bank treasury.	To perform a digital maturity assessment to determine the maturity level of a treasury.	It ensures the right activities and digital technologies are identified for DT.

Table 2. *Cont.*

# Paper (See Supplementary Materials)	Outcome	Assessment Tool Included in the Article	Methodology	Validation Method	Drivers	Dimensions	Industry	Objective	Contribution
18	Maturity model	No	Qualitative	CS	Skills development, project management, agile software development, architecture integration, IT strategy management.	Strategic governance, information and technology, digital process. transformation, workforce management.	Manufacturing.	To analyze how DT capability maturity model identifies organizations 'current DT maturity level. To provide roadmaps for DT maturity improvement. Apply the DT capability maturity model to verify its usability.	Provides guidance and promotes continuous improvement of the lifecycle for DT processes in an efficient and organized way.
19	Assessment tool	No	Empirical	CS	BD, AM, IoT, CPS, automation, robotics, cybersecurity, product and process simulation.	Strategy, people, processes, technology and integration.	General SMEs.	Propose an assessment tool (questionnaire) for evaluating SME's digital readiness and apply it for a case study.	Provides support and understanding to SMEs in their DT journey.
20	Framework	Scorecard template	Qualitative and quantitative	CS	E-Kanban, control systems, AGV, tracking systems, laser welding.	Financial, organizational, and technological.	Automotive.	A multi-criteria decision-making model and framework. Explores criteria and methods that can be used in a feasibility analysis decision-making model for identifying the technologies for effective DT.	Includes business-related financial issues to the model. It serves strategy makers and the knowledge based on multi-criteria technology selection.

Table 2. *Cont.*

# Paper (See Supplementary Materials)	Outcome	Assessment Tool Included in the Article	Methodology	Validation Method	Drivers	Dimensions	Industry	Objective	Contribution
21	Readiness assessment	No	Qualitative	LR, CS	NA	Strategy, governance, operations, object.	Manufacturing.	Develop a readiness model that assesses the capability to use data in industrial enterprises.	Provides information about organizational and structural readiness for data utilization. It assesses the data utilization capability.
22	Maturity model	Questionnaire	Qualitative and quantitative	Delphi method, pilot testing	CPS, IoT, BD, VR, AR, simulation, smart manufacturing, HMI, robotization, manufacturing execution systems.	Service, operations, quality, products, documented information—big data, leadership and strategy, communication, culture and staff.	Manufacturing in SMEs.	Establish a I4.0 maturity model for manufacturing SMEs.	It can be applied in any industry. Determines the degree of implementation compliance of companies in the same sector. Presents the dimensions holistically, considering important criteria. The model is detailed for SMEs to self-assess themselves.
23	Framework	No	Qualitative	LR	Autonomous operation, IT infrastructure, digital twin, role of people and willingness, strong partnerships and connections, I4.0 strategy, financial resources, data Utilization.	Physical and virtual world, human, strategy and culture, products and services, value chain, and the broader environment.	Manufacturing.	Renews the Company Compass 2.0 model by developing a I4.0 conceptual framework and maturity assessment solution to support I4.0 progression.	It is a holistic approach. It determines the deficiencies and gaps of I4.0 organizations readiness level and provides guidelines for improvement.

Table 2. *Cont.*

# Paper (See Supplementary Materials)	Outcome	Assessment Tool Included in the Article	Methodology	Validation Method	Drivers	Dimensions	Industry	Objective	Contribution
24	Maturity model	Questionnaire	Qualitative and empirical	LR, pilot testing	Strategic management, skills acquisition, CC, autonomous equipment, AR, embedded software, real-time data analytics.	Organizational strategy, structure and culture, workforce, smart factories, smart processes, smart products and services.	Manufacturing.	Develops a maturity model 4.0 to support companies in their implementation strategies.	It provides support for initial diagnosis and establishes a roadmap for implementation.
25	Assessment tool	No	Qualitative	LR, CS	Customer orientation, leadership, training of employees, robots, flexible manufacturing, CPS, IoT, BD.	Strategy, structure and organizational culture, workforce, smart factories, smart processes, smart products and services, technology.	Automotive supply chain.	Present and apply questionnaires to analyze the companies' results in I4.0 and the supply chain context.	Collaborates with business areas to help with the understanding and implementation of I4.0 technologies.
26	Readiness assessment	No	Qualitative	CS	Mass product customization, cloud solution, IT and data security, people capabilities, collaboration, inventory control, supply chain integration, flexibility and visibility, real-time data, intellectual property, contracting models.	Products and services, manufacturing and operations, strategy and organization, supply chain, business model, legal considerations.	Supply chain.	Present a readiness self-assessment templates tool to determine the I4.0 of a company while providing a benchmark of I4.0 readiness.	Helps verify companies that are using the opportunities of cyber–physical age present in a proactive and effective way.

Table 2. *Cont.*

# Paper (See Supplementary Materials)	Outcome	Assessment Tool Included in the Article	Methodology	Validation Method	Drivers	Dimensions	Industry	Objective	Contribution
27	Maturity model	Questionnaire	Qualitative and quantitative	LR, CS	Adaptive robotics, data analytics, AI, simulation, embedded systems, communication and networking, cybersecurity, cloud, AM, virtualization, sensors and actuators, RFID and RTLS technologies, mobile technologies.	Smart products and services, smart business process, strategy and organization.	General.	Propose an I4.0 maturity model, discuss the problems with I4.0 implementation, explain reasons to implement and its benefits and to explain and compare existing maturity models.	Smart finance, smart marketing and human resources were proposed to differentiate the model and help organizations broad their perspective for I4.0 applications.
28	Roadmap	No	Qualitative	LR	Data security, digital devices, flexibility in producing products/services, internet connection, collect data, data usage, collaboration.	Production and operations, digitalization, and ecosystem.	SMEs in manufacturing and construction.	Present the approach used to develop a self-assessment tool that determines I4.0 readiness of craftmanship SMEs organizations.	Provide evidence on the design of assessment tools regarding I4.0 readiness in SMEs craftmanship organizations.
29	Roadmap	No	Qualitative	LR	Digital collaboration, digital skills training, business and IT synergy, process standardization, security and legal issues.	Culture, ecosystem, operations, governance, and strategy.	IT companies.	To develop dimensions and criteria for a DT maturity model for IT companies.	Provides understanding of critical areas that are impacted by DT. Provides new ways for a DT assessment specifically for the needs of IT companies.

Table 2. *Cont.*

# Paper (See Supplementary Materials)	Outcome	Assessment Tool Included in the Article	Methodology	Validation Method	Drivers	Dimensions	Industry	Objective	Contribution
30	Assessment tool	No	Qualitative	LR	Leadership, governance structure, IT team, collaboration, automated data, training program, communication, patient-focused plan and innovation plan.	Checklist for organizational, training, technical, cultural, management and further improvement.	Healthcare	To develop a checklist that defines the steps for electronical medical records implementation and DT for hospitals	Provides guidance in preparing hospitals for the implementation of electronic medical records. Separates the readiness for electronical medical records and for DT.
31	Assessment tool	Questionnaire and roadmap	Empirical	CS	I4.0 strategy, indicators, investment plan, IT infrastructure, data collection, autonomous control, ICT functions, data analytics, data-based services, personalization, ICT employee skills, continuous training.	Self-assessment platform for strategy and organization, smart factory, smart operations, smart products, data-driven services, and human resources.	General SMEs.	Present a self-assessment tool that evaluates I4.0 readiness level of a company.	The tool provides a report/roadmap that guides companies with an action plan and recommendations.
32	Framework	No	Qualitative and quantitative	CS	IoT, BD, cloud and mobile technologies, VR, AR, robotics, customer journey, organizational culture, resource management, innovation capacity, improvement goals, flexibility.	Technology, customer, governance, and capability.	Business process management.	Develop a framework for self-assessment regarding the evaluation of business process management software in the DT.	Describes how business process management dimensions are related to DT and demonstrates how analytic hierarchy process can serve for selecting a business process management software.

Table 2. *Cont.*

# Paper (See Supplementary Materials)	Outcome	Assessment Tool Included in the Article	Methodology	Validation Method	Drivers	Dimensions	Industry	Objective	Contribution
33	Framework	No	Qualitative	LR	Telecommunication technology, people, platform, process, device, station, work unit, enterprise and connected world.	Hierarchical and aspect.	Oil and gas industry.	To develop a readiness assessment framework of mobile CC in the upstream oil and gas industry.	Oil and gas industry are assessed accurately. Provides flexibility in the adoption stages.
34	Framework	No	Empirical	CS	E-governance, collaborative platforms, software, data protection, data sharing, digital infrastructure, cloud storing.	Entities, relationships, and activities.	Agriculture.	To outline a framework to operationalize the concept of socio-cyber–physical system with the research and innovation approach and SDGs.	Provides insights on the multifaceted impacts of digitalization.
35	Framework and Readiness Assessment	No	Review DEMATEL	CS	NA	Business models and products; market and sales; value chains and operations; it infrastructure; legal and security; organization and strategy.	Manufacturing and services.	To propose a framework to assist industries in promoting Industry 4.0 through two phases.	Combines an analysis of a firm's readiness level with its corresponding barriers to Industry 4.0 implementation and proposes a series of sequential steps to be carried out for industries seeking to implement Industry 4.0 in their organization.
36	Framework	No	Review, conceptual paper	LR	RAMI 4.0, Standards I4.0 Ontology.	Hierarchy level, lifecycle and value stream, layers.	Manufacturing.	Calculate the readiness and maturity levels of the institution accordingly to RAMI 4.0 framework.	The questionnaire consists of the gathering of the definition of adherent or not adherent to each one of the RAMI and 142 standards.

Table 2 shows the categorization of assessment instruments in terms of maturity models, roadmaps, frameworks, readiness assessments, questionnaires, surveys and/or checklists. These outcomes are helpful given the type of assessment instrument that could be further developed after this research. Overall, 14 out of the 36 papers included a survey, questionnaire, or checklist, while 5 out of the 16 did not show all the questions or are not available at all. This is an important factor because there is a clear need for accessible tools that help assess companies in their digital transformation and Industry 4.0 implementation.

Papers presenting a full questionnaire are described as follows. Pirola et al. [22] propose an assessment model that focuses on small and medium-sized enterprises. The model includes 46 questions that tackle different areas such as strategy, people, processes, technology, and integration. In addition, the model evaluates technologies such as information technology infrastructure, data analytics and security, Internet of Things and cyber–physical systems, automation, and robotics, among others. It also emphasizes investment plans for certain Industry 4.0 concepts. These can be considered as technological drivers for small and medium-sized enterprises.

Dutta et al. [34], are also focused in the small and medium-sized enterprises in manufacturing. The authors developed a survey that helps assess organizations in terms of technology adoption with the goal of achieving business benefits such as increasing productivity, efficiency, and quality. In contrast with other instruments, this survey does not consider organizational, strategic or workforce elements. Its focus is more on production, services and infrastructure. The article highlights the importance of system vertical integration infrastructure, which is one of the main drivers identified in the literature.

Santos and Martinho [14] consider transformation capabilities (drivers) for each dimension. These capabilities provide a clear insight into what must be considered for the dimension to thrive. For example, the workforce dimension includes existent and required skills, skills acquisition, flexibility and autonomy, and creativity and labor enrichment. This can help a company lead its way to Industry 4.0 implementation. Akdil et al. [11] also considered different principles (real-time data, virtualization, decentralization, and agility among others) and technologies (like adaptive robotics, embedded systems, cybersecurity, cloud, additive manufacturing, mobile technologies, etc.) for each dimension to provide an assessment criterion of a maturity model for Industry 4.0.

The questions that Santos and Martinho [14] incorporate are divided by dimension; this is a valuable attribute to the company since it makes it easier to answer them. The dimension that has more questions arethe strategy, structure, and organizational culture 8. The questions within this dimension involve investment plans, Industry 4.0 competitiveness, innovation and the incorporation of new technologies, customers, and clients, among others.

Moreover, Vasconcellos et al. [35] presented a questionnaire that involves dimensions like strategy, structure and organizational culture, workforce, smart factories, intelligent processes, smart products and services, and technology. The relevant dimensions described in this article are strategy, structure, organizational culture (the same as Santos and Martinho [14]), and smart products and services. Some of the leading technologies they are considering Artificial Intelligence, embedded systems, microchips for traceability, additive manufacturing, smart sensors, big data, cloud manufacturing, data security, and augmented and virtual reality. The questionnaire was applied to three different companies considered to be major within the auto parts supply chain, and it was answered by professionals in the continuous improvement area.

Furthermore, Agostino and Costantini [36] proposed a measurement framework by assessing the digital transformation of cultural institutions through a questionnaire. The dimensions this study includes are people, technology, process, customer, strategy, and investment. The questions are divided by dimension, and each dimension has its subcategory. Also, the questions revolve around employees' skills, technology, and data, informatic systems, digital marketing, and strategic planning.

Ávila-Bohórquez and Gil-Herrera [15] focused their study on small and medium-sized enterprises, specifically in manufacturing. These authors include leadership as a dimension that evaluates the existence of roles and responsibilities for leading digital initiatives in the company, the vision of senior managers for digitalization, and the collaboration among stakeholders. These criteria greatly affect the implementation process because it is not just about technology but also about roles, skills, and leadership.

Particularly, Pirola et al. [22], Santos and Martinho [14], Vasconcellos et al. [35], and Ávila- Bohórquez and Gil-Herrera [15] carried out studies that contain information about relevant dimensions, questionnaires, industry of application, and other fundamental elements for developing a more robust assessment instrument.

This study has also taken a deeper analysis of the assessment instruments proposed by the 36 papers in Table 2. The authors have identified the dimensions and drivers for the Industry 4.0 digital transformation that are addressed in these papers. This analysis is shown in Tables 3 and 4. Furthermore, it identifies how the experts have been addressing and enhancing assessment industries throughout the last few decades.

Table 3. Analysis of assessment instruments by dimensions and drivers (16 out of 36 articles).

Characteristic	**Bastos et al. (2021) [18]**	**Agca et al. (2017) [31]**	**Gökalp et al. (2017) [23]**	**Isaev et al. (2018) [37]**	**Akdil et al. (2018) [11]**	**Brozzi et al. (2018) [38]**	**Scott et al. (2019) [39]**	**Pirola et al. (2019) [22]**	**Schumacher at al. (2019) [40]**	**Aripin et al. (2020) [25]**	**Brkić et al. (2020) [41]**	**Castro et al. (2020) [33]**	**Gollhardt et al. (2020) [12]**	**Santos and Martinho (2020) [14]**	**Nausch et al. (2020) [42]**	**Beyaz and Yıldırım (2020) [43]**
Dimensions																
Smart factory	x											x		x		
Process			x		x			x	x					x		
Product	x	x			x	x			x			x		x	x	x
Strategy	x	x		x	x			x	x			x	x	x	x	
Technology	x			x		x	x	x	x		x					x
Customers/Clients				x					x		x					
Employees/Workforce							x	x	x			x		x		
Leadership									x							x
Governance/Policy		x	x						x		x		x		x	
Organization		x	x	x	x		x					x		x		x
Operation	x	x		x		x						x	x		x	
Culture							x						x	x		
Supply chain		x														
Services		x			x							x		x		
Others	x									x						

Table 3. *Cont.*

Drivers	Bastos et al. (2021) [18]	Agca et al. (2017) [31]	Gökalp et al. (2017) [23]	Isaev et al. (2018) [37]	Akdil et al. (2018) [11]	Brozzi et al. (2018) [38]	Scott et al. (2019) [39]	Pirola et al. (2019) [22]	Schumacher at al. (2019) [40]	Aripin et al. (2020) [25]	Brkić et al. (2020) [41]	Castro et al. (2020) [33]	Gollhardt et al. (2020) [12]	Santos and Martinho (2020) [14]	Nausch et al. (2020) [42]	Beyaz and Yildirim (2020) [43]
General drivers				x											x	
Cyber–physical systems	x							x	x	x						
Horizontal and vertical integration		x							x							
Employee's willingness, skills, roles, and Flexibility		x	x			x	x		x	x	x	x	x	x		
Embedded systems	x				x				x					x		
ICT infrastructure	x					x				x		x				x
Sensors and/or tracking devices	x				x				x							x
Innovation							x				x					
Key performance indicators	x											x				
Coordination and collaboration	x	x			x	x	x				x		x			
Cloud computing	x	x	x		x						x			x		
Big data, data analytics, and/or data management and technology	x	x	x		x	x	x	x			x	x		x		
Internet of Things	x		x					x			x					

Table 3. *Cont.*

Drivers	Bastos et al. (2021) [18]	Agca et al. (2017) [31]	Gökalp et al. (2017) [23]	Isaev et al. (2018) [37]	Akdil et al. (2018) [11]	Brozzi et al. (2018) [38]	Scott et al. (2019) [39]	Pirola et al. (2019) [22]	Schumacher at al. (2019) [40]	Aripin et al. (2020) [25]	Brkić et al. (2020) [41]	Castro et al. (2020) [33]	Gollhardt et al. (2020) [12]	Santos and Martinho (2020) [14]	Nausch et al. (2020) [42]	Beyaz and Yildirim (2020) [43]
Management		x									x			x		
Simulation					x			x								
Robots	x				x						x					x
Strategy																
Cybersecurity		x	x		x	x		x					x			
Automation	x		x				x	x				x		x		
Augmented reality											x			x		
Virtual reality											x					
Artificial Intelligence	x				x											
Additive manufacturing	x				x											
Mass customization	x	x					x					x				
Includes a questionnaire, survey or checklist				x	x		x	x	x			X		x		
# of questions	-	-	-	29	68	-	19	46	65	-	-	-	-	41	-	-

Table 4. Analysis of assessment instruments by dimensions and drivers (20 out of 36 articles).

Characteristic	Dutta et al. (2020) [34]	Vasconcellos et al. (2021) [35]	Nick et al. (2021) [44]	Gökalp and Martinez (2021) [45]	Von Solms and Langerman (2021) [46]	Kruszyska-Fischbach et al. (2021) [47]	Machado et al. (2021) [48]	Agostino Costantini (2021) [36]	Caiado et al. (2021) [49]	Kusmiarto et al. (2021) [50]	Amaral and Peças (2021) [51]	Metta et al. (2022) [52]	Ávila-Bohórquez and Gil-Herrera (2022) [15]	Han et al. (2022) [53]	Kırmızı and Kocaoglu (2022) [54]	Nenadál et al. (2022) [55]	Szelągowski and Berniak-Woźny (2022) [56]	Kayikci et al. (2022) [57]	Prashar (2023) [58]	Govindan K. et al. (2023) [59]
Dimensions																				
Smart factory		x																		
Process		x			x			x			x			x	x	x	x	x	x	x
Product	x	x	x						x		x		x					x	x	
Strategy	x	x	x				x	x		x			x		x	x		x	x	x
Technology	x	x	x	x	x	x	x	x		x	x					x		x	x	x
Customers /Clients								x	x											x
Employees/Workforce		x	x	x	x			x		x	x				x	x			x	
Leadership					x					x			x							
Governance/Policy				x						x					x		x	x		
Organization						x					x				x		x		x	x
Culture		x								x			x		x	x			x	
Operation													x							x
Supply chain																				
Services	x	x	x										x						x	
Others												x								

Table 4. *Cont.*

Drivers	Dutta et al. (2020) [34]	Vasconcellos et al. (2021) [35]	Nick et al. (2021) [44]	Gökalp and Martinez (2021) [45]	Von Solms and Langerman (2021) [46]	Kruszyska-Fischbach et al. (2021) [47]	Machado et al. (2021) [48]	Agostino Costantini (2021) [36]	Caiado et al. (2021) [49]	Kusmiarto et al. (2021) [50]	Amaral and Peças (2021) [51]	Metta et al. (2022) [52]	Ávila-Bohórquez and Gil-Herrera (2022) [15]	Han et al. (2022) [53]	Kırmızı and Kocaoglu (2022) [54]	Nenadál et al. (2022) [55]	Szelągowski and Berniak-Woźny (2022) [56]	Kayikci et al. (2022) [57]	Prashar (2023) [58]	Govindan et al. (2023) [59]
General drivers										x										
Cyber–physical systems	x	x											x					x		
Horizontal and vertical integration														x	x			x		
Employee' s willingness, skills, roles, and flexibility		x	x	x			x	x			x						x	x	x	
Embedded systems																	x			
ICT infrastructure			x	x			x	x			x	x						x	x	
Sensors and/or tracking devices																x				
Innovation											x									
Key performance indicators	x										x									
Coordination and collaboration			x			x	x				x	x								
Cloud computing	x				x	x			x			x		x						
Big data, data analytics, and/or data management and technology	x	x	x		x		x	x				x	x		x	x				
Internet of Things	x	x											x			x				

Table 4. *Cont.*

Drivers	**Dutta et al. (2020) [34]**	**Vasconcellos et al. (2021) [35]**	**Nick et al. (2021) [44]**	**Gökalp and Martinez (2021) [45]**	**Von Solms and Langerman (2021) [46]**	**Kruszyska-Fischbach et al. (2021) [47]**	**Machado et al. (2021) [48]**	**Agostino Costantini (2021) [36]**	**Caiado et al. (2021) [49]**	**Kusmiarto et al. (2021) [50]**	**Amaral and Peças (2021) [51]**	**Metta et al. (2022) [52]**	**Ávila-Bohórquez and Gil-Herrera (2022) [15]**	**Han et al. (2022) [53]**	**Kırmızı and Kocaoglu (2022) [54]**	**Nenadál et al. (2022) [55]**	**Szelągowski and Berniak-Woźny (2022) [56]**	**Kayikci et al. (2022) [57]**	**Prashar (2023) [58]**	**Govindan et al. (2023) [59]**
Management				x											x	x			x	
Simulation	x												x							
Robots	x	x			x								x							
Strategy																				
Cybersecurity												x			x					
Automation			x		x															
Augmented reality		x				x							x							
Virtual reality													x							
Artificial Intelligence					x	x														
Additive manufacturing	x																			
Customization																			x	
Includes a questionnaire, survey or checklist	x	x				x	x	x		x			x							
# of questions	-	66	-	-	-	32	70	19	-	67	-	-	49	-	-	-	-	-	-	36

4. Discussion

The burgeoning landscape of Industry 4.0 (I4.0) adoption necessitates robust and standardized measures of organizational readiness. This review evaluated Industry 4.0 assessment tools for organizational readiness, revealing strengths, limitations, and emerging trends. Our analysis discussed key findings, including factors that influence readiness and trade-offs with different tool designs.

There are seven main findings drawn by this study:

a. First, one of the key findings is the identification of relevant literature resources for assessing digital transformation in Industry 4.0. Tables 2 and 5 provide insights derived from their analysis.
b. Second, another key discovery is the recognition of drivers and dimensions (refer to Tables 3 and 4) as crucial constituents in crafting an assessment tool for Industry 4.0 digital transformation. Table 6 elaborates on each dimension identified, namely strategy, technology, product, culture, service, process, operation, organization, governance, and operation.
c. Third, the technological and organizational Industry 4.0 drivers were considered in Tables 3 and 4. These included leadership and collaboration, vertical integration, and data analytics and management.
d. Fourth, the SLR highlights the importance of data analytics and management to be implemented correctly and considered to create the best practices for an assessment instrument for digital transformation.
e. Five, there are only three papers focused on the automotive industry, and only one contains a detailed questionnaire focused on assessing digital transformation in a company. This creates an opportunity to design a new tool that covers this gap.
f. Six, this study takes a holistic view of assessment instruments and constructs defined as maturity models, roadmaps, frameworks, readiness assessments, questionnaires, checklists, and surveys by clarifying the diverse tools used when implementing Industry 4.0.
g. Seven, there is a lack of studies in this area in some geographical regions such as Canada, Africa, and Central America.

Table 5. Key research insights and trends.

Category	Key Insights
Assessment Tools	-Combine Industry 4.0 and circular economy for sustainable practices.
	-Guide companies through digital transformation.
	-Help SMEs and low-maturity companies assess themselves.
	-Provide more reliable process maturity assessment than traditional models.
	-Develop questionnaires and frameworks for practical assessment.
	-Analyze data utilization and support technology selection.
	-Demonstrate tool effectiveness through case studies.
Industry-Specific Applications	-Adapt models services, operations/supply chain, and Quality 4.0.
	-Identify Industry 4.0 priorities for Indian manufacturing SMEs.
	-Develop e-readiness models for healthcare and cost consultation.
	-Assess data utilization capabilities in industrial enterprises.
	-Create maturity models for specific sectors like manufacturing and IT.
Other Research-Related Areas	-Propose design theory-based framework for new maturity models.
	-Examine e-readiness factors in healthcare and develop implementation checklists.
	-Offer self-assessment tools for Industry 4.0 readiness and BPM software evaluation.
	-Explore mobile cloud computing readiness in oil and gas and operationalize socio-cyber–physical systems.

Table 6. Dimensions' and drivers' description.

#	Dimension	Description	Industry 4.0 Drivers
1	Strategy	To improve an organization through innovation culture, continuous improvement, implementation of new information and technologies, efficient organizational structure, and client satisfaction. It is considered the "input" for the transformation of Industry 4.0. Development of new smart products, services, and business operations and promote collaboration between stakeholders that fosters progress, structure, and leadership.	Business models Strategic partnerships and collaborations Technology investment Leadership Focus on organizational tasks, employee autonomy, motivation, and team skills. Customer orientation Adaptation to technological changes
2	Workforce	Implementing and developing suitable technical and management skills is necessary for digital transformation. Also, the willingness, autonomy, openness of the workforce, and flexibility are fundamental aspects of rapid Industry 4.0 changes.	New and better qualifications Learning platforms Appropriate training using technological tools. Digital thinking
3	Leadership	Implementing a vision or strategy for encouraging digital technology and drivers is necessary for this dimension. Organizational alignment to adopt Industry 4.0 concepts.	Communication of Industry 4.0 plans Willingness to realize Industry 4.0 Critical thinking Management of employees
4	Clients	Enhancing a client's relationship with the company and their satisfaction are essential parts of this dimension. The ability to engage with clients and maintain effective communication.	Information technology-enhanced collaboration Digital contacts of clients Openness to new technology Client integration into product/service development Data utilization
5	Smart factories Smart services	To include technologies that promote real-time communication between machines, products, people, and infrastructure. Smart factories are composed of smart sensors and actuators, embedded systems, and connectivity. Smart services present wide digitalization and real-time connectivity and information.	Man–machine interaction. Robots Integration and operation Simulation, digital twins Cyber–physical systems, Industrial Internet of Things, Service Internet of Things
6	Smart products and services	Implementing products with embedded systems are the foundation for real-time data collection, promoting communication between customers, factories, and value chain processes. It measures the characteristics of the products and services that are driven by data.	Products and servers enabled by IT systems. Customer orientation Mass product customization Data-driven services. Digital product features Product data usage Share of revenue
7	Technology	To implement smart factories and processes, it is necessary to use interconnected technologies (cyber–physical systems, Internet of Things, big data, big data analytics, and cloud manufacturing)	Self-managed traceability systems Simultaneous communication between machines, products, and processes Communication between factories and supply chain Manufacturing optimization
8	Governance	To follow and comply with regulations and rules. It creates suitable structures to manage the organization's operation.	Corporate social responsibility Data management Data utilization engagement Analytical abilities

Table 6. *Cont.*

#	Dimension	Description	Industry 4.0 Drivers
9	Operations	To manage, measure, and control the processes and services of the company. It includes the technologies that enhance their productivity.	Technology integration Automation Data utilization Resource capability
10	Supply chain	To promote visibility and connection between several business functions by implementing advanced technology across the supply chain. An integrated supply chain connects suppliers and customers. It is required to develop processes, capabilities, and systems to support digital collaboration.	Inventory control Real-time data management Supply chain integration, flexibility, and visibility Lead times

The criteria considered in the different tools (maturity models, roadmaps, frameworks, and readiness assessment, questionnaires, checklists, and surveys) found in the literature were helpful to provide insightful information about how an assessment instrument can help to diagnose a company in terms of Industry 4.0, the industry where it is applied, and the technologies that are considered.

To further elaborate on the first point and comprehensively answer RQ1, Table 5 presents some observations that can be derived by combining the information from the papers chosen in the SLR (see Table 2) and classified into three categories.

To provide a thorough response to RQ2 and further elaborate on the second point, it has been concluded through the SLR that evaluating Industry 4.0 digital transformation requires the consideration of dimensions and their drivers as key components. Consequently, 10 dimensions have been identified, including *strategy*, *technology*, *product*, *culture*, *service*, *process*, *operation*, *organization*, *governance*, *and operation* (as outlined in Tables 3 and 4). A detailed description of each dimension and its corresponding drivers can be found in Table 6.

The strategy dimension is the most used dimension followed by technology. Pirola et al. [22] include strategy and technology as dimensions in their assessment instrument. They evaluate strategy by analyzing if the organization includes plan of actions focused on the digitalization and incorporation of Industry 4.0 principles. On the other hand, they evaluate the technology dimension by analyzing the current adoption of Industry 4.0 enabling technologies, e.g., the Internet of Things, cyber–physical systems, robotics, automation, cloud, and big data, among others.

The remaining dimensions (workforce, leadership, clients, smart factories, smart products and services, governance, operations, and supply chain) are the most common ones retrieved in the 36 research articles. Ávila-Bohórquez and Gil-Herrera [15] define the "operations" dimension as the processes, actions, methods, and technology impacting the organization's productivity. Their proposal includes operational questions that focus on components such as automation, integration, and methodology implementation, among others.

Another important dimension for Industry 4.0 and digital transformation is governance, which refers to an organization that abides by established rules and regulations. Kimirzi and Kocaoglu [54] used governance as part of their maturity model and evaluated its capability items such as top management participation, consultancy, regulations, data, and information sovereignty, among others. Other authors, such as Nausch et al. [42] and Brkić et al. [41], also use governance to manage digital transformation in industries such as manufacturing and business process management.

The dimension smart services and products consider the use of artificial intelligence in products and services, which may help identify ways to improve and optimize the digital supply chain, adding real value. The most important issue is how companies can obtain information about the process of a product/service, and recording the status and location of these can help monitor the production line and identify bottlenecks and current needs. The use of databases, the cloud, or any other digital infrastructure to store information can help in the decision making and prevent production/service errors.

That means having a digital product design allows an accurate representation of information and allows control over a product before it is physically developed. For instance, simulation and digital twins technology allows for testing the product in different ways (strain, stress, ductility, etc.) and verifying if changes need to be made. Having the ability to adapt to customer orders is an important Industry 4.0 concept.

The supply chain dimension refers to how to maintain the stability and continuous improvement in the entire value chain when organizational communication and collaboration are relevant drivers to maintain throughout the whole process of the digital supply chain and the supply chain networks. If real-time information is provided, then the level of assessment is at its highest, because it optimizes and reacts to changes in demand in an agile way. The inventory must be monitored at all times due to the costs that it can incur. The level of assessment can vary from unknown to updated in real time and automatically recorded in a database. Production must be monitored, and the department/area needs to indicate when a change in production is required.

Furthermore, sustainability through the entire Supply Chain 4.0 must be considered in the company; thus, its level must be assessed. The traceability of the product throughout the value chain provides information about its status and condition, which helps the company analyze future improvements and helps in the decision-making process. The involvement of clients and suppliers in the design and fabrication of products can promote better collaboration between the stakeholders. Also, it will reduce the time and cost of production.

Moreover, Ávila-Bohórquez and Gil-Herrera [15] include leadership as a dimension that evaluates the existence of roles and responsibilities for leading digital proposals in the company, the vision of senior managers for digitalization and the collaboration among stakeholders. These criteria greatly affect a company because when implementing Industry 4.0 concepts, it is not only about technology but also about roles, skills, and leadership.

The workforce dimension defines how training and evaluating employees for Industry 4.0 keeps the company capable of using and adopting technologies that help the company grow. Also, by indicating how often the training program is updated and promoting constant learning, continuous improvement is encouraged. The flexibility and creativity of an employee promote a better company environment and an engagement toward their roles and responsibilities. The emergence of new roles and job positions will help employees adapt to new technologies faster and help combine information between areas, identifying barriers in the workforce to help companies find solutions and areas of opportunity.

Other Considerations When Elaborating an Assessment Instrument

When defining an assessment instrument, it is important to include the maturity model perspective given that it evaluates the progress of a specific ability or a company's objective: in this case, an Industry 4.0 goal. Also, it has the purpose of helping improve their technologies, strategies, and capabilities in different dimensions of the organization.

Moreover, it assesses the company through a set of guided questions that measure their maturity level. Another important factor to consider before filling in the assessment instrument is that the company must have basic Industry 4.0 knowledge. Also, it is necessary that the organization has managers and/or experts from their corresponding department/area so that the results are more accurate in the current situation of the company.

Furthermore, the organization must verify the company's readiness for Industry 4.0 implementation before applying the proposed one, since it is considered a maturity model and does not evaluate the state of being ready. After answering the model, a roadmap can be developed by considering the results from the instrument.

5. Conclusions

The concepts of Industry 4.0 and digital transformation are rapidly gaining traction and are significantly impacting technology, strategy, organization, the environment, and the economy. These concepts are transforming the way in which businesses, governments, and individuals operate. They entail the integration of physical and virtual worlds through cutting-edge technologies such as big data, automation processes, cloud computing, hardware, and software systems.

However, businesses are overwhelmed by the rapid progression as they struggle to conduct Industry 4.0 initiatives correctly. Not understanding the implications and effects brings uncertainty to developing and implementing action plans. Thus, there is a clear need for guidance and ways to assess digital transformation in companies.

We highlight two main contributions of this study:

a. The application of the PRISMA methodology has yielded notable outcomes, providing a thorough and all-encompassing examination of critical evaluation tools, including maturity models, frameworks, roadmaps, and readiness assessments. As a result, supplementary instruments, such as questionnaires, surveys, and checklists, have been incorporated. Additionally, these findings have been scrutinized to discern essential observations about present research emphases and potential prospects for future exploration, all of which are interrelated with RQ1.
b. While crafting an assessment tool for Industry 4.0 digital transformation, an important discovery was made regarding the significance of "drivers" and "dimensions" as crucial components, answering RQ2. These ten dimensions, along with their corresponding drivers, can be utilized as a foundational framework to design a survey that can assist businesses in assessing their progress in Industry 4.0.

These are three aspects that managers involved in Industry 4.0 digital transformation projects should consider:

a. There is a wide range of assessment instruments that can guide the implementation of Industry 4.0 by identifying what the company needs to focus on and helping prioritize the areas of opportunities regarding Industry 4.0 digital transformation.
b. Using these assessment instruments requires basic training on what Industry 4.0 is.
c. Selecting a proper assessment instrument supports investing appropriately and allocating resources according to the objectives, improving key performance indicators, and overall, enhancing their performance, productivity, and sales.

The following avenues of future research are proposed to continue this study:

a. An extended SLR can include studies in other languages besides English.
b. Developing an assessment instrument might fill the gap in the literature of current tools that evaluate the implementation of Industry 4.0 in companies.
c. Qualitative studies, such as interviews and focus groups, can be used to formulate appropriate questions for each of the ten different dimensions: strategy, workforce, leadership, clients, smart factories, smart products and services, technology, operations, governance, and supply chain. The drivers associated with each dimension should also be considered.
d. Validation of the instrument can be completed via interviews with experts or conducting a case study based on the use of the proposed instrument.
e. The instrument may become more user-friendly and efficient by developing a digital interface that allows information and data to be stored in real time. Thus, results can be visually accessed from a platform (e.g., a dashboard).
f. To implement a mixed-quantitative method to make this study more flexible and precise, aligned with the company´s goals, and easier to interpret. For example, depending on the company, some questions are more important or impactful than others. Suppose the organization assigns the questions a numerical value depending on its priority. In that case, they can identify what areas are the ones that they should focus on and develop a plan or roadmap depending on that.

g. Include quantitative methods such as fuzzy logic, Spherical Fuzzy COPRAS, Analytical Hierarchy Process, and intra-class correlation to help integrate qualitative and quantitative data.
h. Finally, the instrument can be further adapted beyond the manufacturing area, that is, the service industry, such as healthcare.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/app14051693/s1, Table S1: 16 Cases of Study Analysis; Table S2: 36 List of References.

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