Article

Application of Toolbox Diagnosis of Sustainability 4.0 in Manufacturing Operations: Sustainability Integration in the Context of Industry 4.0

Carmen G. Arguelles, Vianey Torres-Arguelles *, Salvador Noriega

Department of Industrial and Manufacturing Engineering, Autonomous University of Ciudad Juárez, Ciudad Juárez 32310, Mexico

* Correspondence: Vianey Torres-Arguelles, Email: vianey.torres@uacj.mx.

ABSTRACT

Background: This paper describes the development of a toolbox for measuring the state of sustainability in industrial plants adopting Industry 4.0 (I4.0), using a diagnosis of Sustainability 4.0 (S4.0) (i.e., the integration of sustainable practices with I4.0 tools) as a business strategy, based on the Sustainable Development Goals (SDGs) of the United Nations (UN).

Methods: The evaluation of sustainable integration with I4.0 practices was based on the development of a toolbox for S4.0, which consisted of two parts with 10 steps. In the first stage of the research, the toolbox was developed, and in the second stage, it was applied to obtain a diagnosis of sustainability integration in the context of I4.0.

Results: We report the development of a toolbox for sustainable manufacturing practices and the tools of I4.0 identified in the literature, which was validated based on expert judgment. The S4.0 toolbox was used to obtain a diagnosis of the integration of such practices in a sample of industrial plants located in Ciudad Juarez, Chihuahua, Mexico.

Conclusions: Our results show that the current level of adoption of S4.0 is 6.36% on average, in the manufacturing sector in Ciudad Juárez, México. This indicates the need to develop strategies for the adoption of sustainable practices.

KEYWORDS: sustainability; Industry 4.0; sustainability practices; toolbox S4.0; sustainability diagnosis

Open Access

Received: 26 August 2023
Accepted: 18 November 2024
Published: 29 November 2024

ABBREVIATIONS

S4.0, Sustainability 4.0; I4.0, Industry 4.0; TB, toolbox

INTRODUCTION

The production and consumption of goods and services are two of the major factors that impact ecosystems, leading to the alteration of biogeochemical cycles, ozone depletion, and ocean acidification [1,2], which have a direct impact on climate change due to the severity of environmental degradation. There is therefore a need to become aware of the seriousness of environmental degradation, which has been increasing since the middle of the 20th century. Faced with these concerns, the United Nations proposed the concept of sustainable development in 1972 as the ability for current populations to meet their actual needs without compromising the ability of future generations to meet their own [3]. In the area of manufacturing, the International Institute for Sustainable Development (IISD) has defined sustainable development as the adoption of business strategies and activities to meet the actual needs of the company and its stakeholders, while conserving, enhancing, and protecting the natural and human resources that will be needed in the future [4].

This means that changes are needed in terms of production and consumption [5], especially in view of the transition of many industries to an Industry 4.0 (I4.0) model [6]. This new industrial paradigm involves the networking of industrial automation systems with innovative functions based on access to the cyber world. It represents a transformation of industrial processes towards digitalisation [7] in order to obtain increases in productivity, income and competitiveness; however, there is a lack of integration of sustainable practices, which limits the resolution of environmental issues to the benefit of production [8,9]. Nonetheless, there is evident potential for the integration of I4.0 technologies with sustainable processes. This can be achieved by identifying and evaluating indicators of industrial activities with significant environmental impacts [6,10].

In Ciudad Juarez, Chihuahua, Mexico, which is located on the international border with El Paso, Texas, USA, the manufacturing sector accounts for 41% of the state's GDP [11]. This area contains close to 350 multinational industrial companies, operating more than 400 plants. The most technologically advanced companies are currently adopting I4.0 practices [10], but the status of the integration and impact of sustainable practices is unknown. For this reason, it is important to characterise the introduction of Sustainability 4.0 (S4.0) in the high-tech factories in Ciudad Juárez. We define S4.0 as the application of I4.0 technological solutions to address the environmental, economic, social, and technological challenges facing our world. In other words, S4.0 combines the principles of sustainable development with the advanced and connected technologies of the fourth industrial revolution, to achieve a sustainable development model.

In this report, we describe the development and application of a toolbox for determining the status of S4.0 of manufacturing firms of different types and sizes in Ciudad Juarez, Chihuahua, Mexico. The specific research questions of our study are:

RQ1: What are the key sustainability indicators (environmental, economic, social and technological) in manufacturing operations that need to be assessed and how can they be measured using Industry 4.0 technologies?

RQ2: Can a toolbox that integrates sustainability and I4.0 tools make it easier to assess the adoption of sustainable practices in manufacturing?

The remaining sections of this study are organised as follows. Section 2 (MATERIALS AND METHODS) explains the materials and methods used to develop the toolbox, and describes the application of this toolbox to obtain a diagnosis of the status of S4.0 in the manufacturing industry in Ciudad Juárez, Chihuahua, México. In Section 3 (RESULTS), we report the results of the validation and the application of the toolbox to generate a diagnosis in terms of sustainability adoption levels. In Section 4 (DISCUSSION), we present our results, and Section 5 (CONCLUSION) contains conclusions and recommendations.

MATERIALS AND METHODS

This section presents the materials used and methods applied in the development and validation of a toolbox that can be used to measure the adoption of S4.0 in manufacturing companies in Ciudad Juárez. The following list summarises the resources used in the project.

- A literature review of studies in the university library and virtual libraries enabled the identification of the sustainability indicators; The FESTO toolbox [12] was used as a basis for the calculation of the I4.0 levels;
- Publisher version 16 was used for the development of the toolkit;
- Minitab version 17 was used for the expert validation analysis;
- Adobe Illustrator was used to develop the images for the toolbox;
- The toolbox was redesigned in PDF Pro version 16 in response to recommendations from the validation experts;
- Electronic means such as computers, cell phones, projectors, and e-mail were used for the application of the toolbox and a satisfaction survey.

The research was conducted in two stages: in the first, the toolbox was developed, and in the second, field measurements were carried out to generate a diagnosis of sustainability in the manufacturing industry. Figure 1 shows the stages of development of this study.

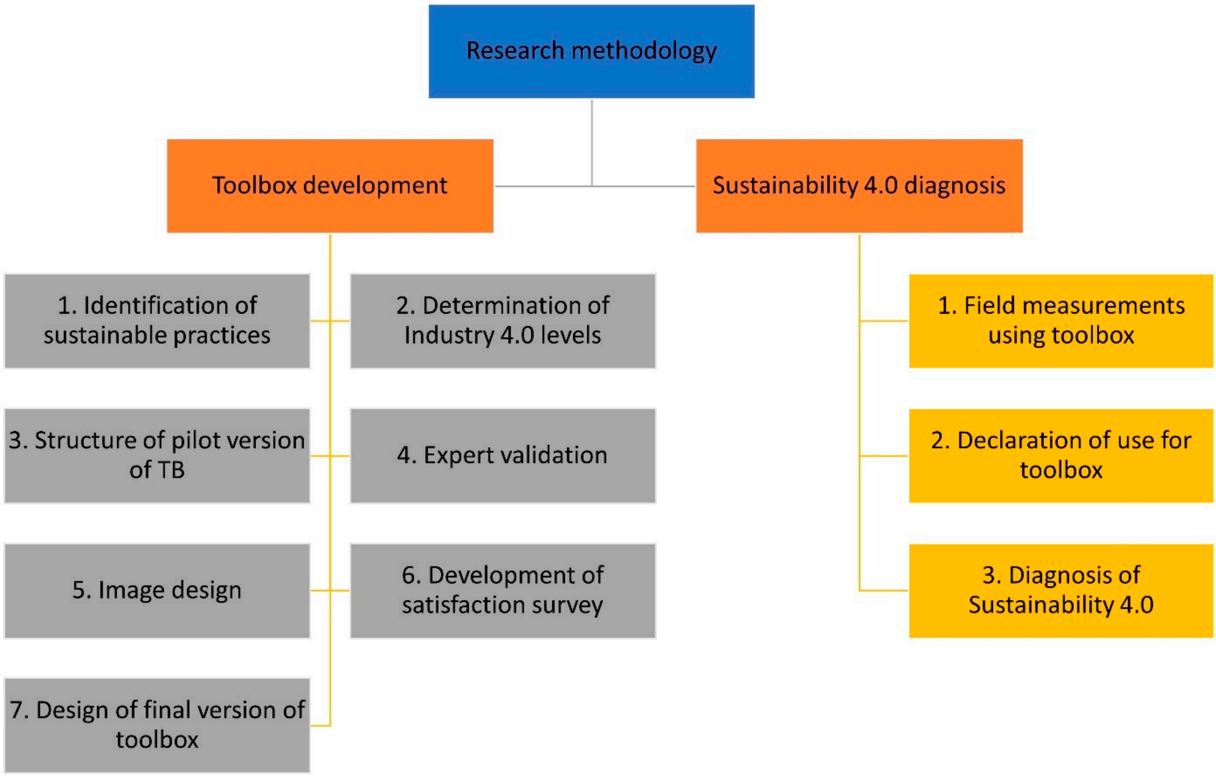

Figure 1. Structure of the methodology for this study.

Development of the Toolbox

The sustainability toolbox was developed in seven steps: (i) identification of sustainable practices; (ii) determination of I4.0 levels; (iii) design of the structure of the pilot version of the toolbox; (iv) expert validation; (v) image design; (vi) development of a satisfaction survey; (vii) production of the final version of the toolbox.

Identification of sustainable practices

To identify the sustainability practices that manufacturing companies should consider, several sources were consulted, including online databases, the virtual library, and the physical library of the Universidad Autónoma de Ciudad Juárez (the Autonomous University of Ciudad Juarez), where keywords were used to select the papers. The keywords were sustainability, sustainability dimensions, sustainability practices, manufacturing industry, I4.0 and I4.0 pillars. In the next level of the search, these words were used in combination, for example sustainability and manufacturing industry, sustainability practices and manufacturing, sustainability and manufacturing industry and I4.0, and sustainability practices and I4.0 pillars. Using these words and their combinations, 413 documents were identified. After reading and analysing these documents, 153 were selected for this study.

Determination of I4.0 levels

The levels used here to measure sustainability are the same as those used in the FESTO toolbox [12] to determine the use of technologies in products and processes. We consider five levels, ranging from 'no use of technology' to 'full automation including one or more I4.0 technologies', to avoid moderate or regular responses (value 3 in a range from 1 to 5), this toolbox proposes to use four measuring levels. These values determine the level of integration of sustainable practices into the pillars of I4.0.

Structure of the pilot version of the toolbox

After identifying and selecting the sustainable practices (32 items) and the four I4.0 levels, the first version of the toolbox was designed. Since the toolbox had to be practical and quick to use, it was divided into two sections: the first collects demographic information such as size and type of industry, while the second collects information on sustainable practices across four dimensions of sustainability: environmental, economic, social and technological.

Expert validation of the toolbox

At the same time as the toolbox interface images were being designed, experts validated the items by evaluating the sustainability indicators considered in the toolbox, and were asked to respond as to whether or not the plants were using them. This method verifies the reliability of a survey. Validation involves the informed opinion of people with experience of the subject who can provide information, evidence, judgments, and assessments [13].

This method consisted of asking experts to provide a judgment on a specific topic [14]. The objectives were to precisely determine the factors that define the sustainable practices within the I4.0 activities, based on to the evaluation, comments, and observations of the experts, and to decide which were relevant in this study and should be included in the measurement tool. We considered two established criteria for validation purposes, clarity and relevance [13], as follows:

- **Clarity**: The item is easy to understand, i.e., the semantics are adequate, with the following options as responses:
- The item is not clear;
- The item requires many changes;
- The item requires a few changes;
- The item is clear and appropriate.
- **Relevance**: The item is essential, i.e., it must be included, with the following options for responses:
- The item can be removed without affecting the dimension;
- The item has some relevance, but it can be the subject of measurement by someone else;
- The item is relatively important;

- The item is very relevant and should be included.

Image design for the toolbox

Adobe Illustrator was used to create interface images, both for the sustainability indicators and for the proposed I4.0 levels. A separate image was designed for each sustainability indicator and level of integration of the corresponding I4.0 tools; this was done in order to offer a visual representation of each answer option, for better understanding.

Development of the satisfaction survey

The usefulness of the toolbox was measured using, four criteria were considered: Measurement, Novelty, Comprehensibility and Modularity; based on eight questions in the form of a questionnaire. A five-point Likert scale was used, with 1 corresponding to “strongly disagree”, 2 to “disagree”, 3 to “neither agree nor disagree”, 4 to “agree”, and 5 to “strongly agree”. The Likert scale is based on ordinal levels [15], and is constructed as a series of questions that are each associated with a fixed value, reflecting the interviewee’s opinion in terms of a degree of agreement or disagreement with a statement. The Likert scale is easy to use, and the results take the form of percentages, which are straightforward to interpret with Cronbach’s alpha in order to determine the reliability of the questionnaire [16]. Cronbach’s alpha estimates the internal consistency of multiple-choice responses, such as the Likert scale; this parameter, in general, determines the reliability of the average of q measurements, which can represent the behavior of the items in a questionnaire.

The satisfaction survey began with the instruction “Please rate your level of agreement with each of the following aspects of the evaluation of the usefulness of the toolbox on a scale of 1 to 5, where 1 means strongly disagree, 2 means disagree, 3 means neither agree nor disagree, 4 means agree, and 5 means strongly agree”.

The questions were as follows:

1. The toolbox is a guide that identifies the aspects that need to be developed to achieve environmentally friendly processes.
2. The toolbox is a suitable self-assessment tool for your organisation’s sustainability parameters.
3. The toolbox can be considered the only one of its kind for sustainability analysis at the I4.0 adoption level.
4. The toolbox has a user-friendly design.
5. The toolbox is easy to understand.
6. The levels of the toolbox clearly explain the level of adoption of I4.0.
7. The toolbox is a good assessment tool for companies in different industries.
8. The toolbox can serve as an evaluation tool for companies of different sizes.

Production of the final version of the toolbox

The final version of the toolbox contained three sections. The first asked for information on the company such as the industry and size, the name of the company, and the position of the person evaluating the usefulness of the measuring instrument. The evaluation section covers the environmental, financial, production and technological areas. The third section is the satisfaction survey, which assesses the usefulness of the toolbox.

Sustainability 4.0 Diagnosis

The level of integration of sustainability in the manufacturing industry was determined using three steps: (i) measurements in the field through the application of the toolbox; (ii) satisfaction survey to assesses the usefulness of the toolbox; and (iii) diagnosis of the S4.0 level.

Measurements in the field through the application of the toolbox

This phase involved participants from a variety of manufacturing plants of multinational companies, in the domains of aerospace, automotive, construction, electronics, communications, computer equipment, office supplies, transportation equipment, medical equipment, pharmaceuticals, integrators, electrical machinery, ferrous metals, non-ferrous metals, plastics and rubber, fabricated metal products, suppliers, and chemicals. The companies were different sizes, including small, medium, and large.

Toolbox usefulness survey

Data analyses were carried out with statistical tools such as Minitab and Excel, including factor analysis and graphing. This allowed us to study of the situation in the manufacturing industry of Ciudad Juarez in terms of sustainability practices and transition towards I 4.0.

Diagnosis of the S4.0 level

The data obtained from the application of the toolbox were analysed with the help of graphs, in order to study the situation of the industrial plants in our sample of companies from the manufacturing industry of Ciudad Juarez, in terms of their sustainable practices related to the transition towards I4.0.

RESULTS

Development of the Toolbox

The sustainability toolbox was developed in the following stages: (i) identification of sustainable practices; (ii) determination of I4.0 levels; (iii) development of the pilot version of the toolbox; (iv) expert validation; (v) image design; (vi) development of the satisfaction survey; (vii) design of the final version of the toolbox.

Identification of sustainable practices

The sustainability indicators were identified based on their relative importance and impact, and a total of 32 indicators were selected. These were organised into four dimensions, environmental (18), economic (4), social (4), and technological (6). The search for indicators was based on the selected keywords and 153 documents were reviewed, classified by sustainability dimension and divided into the following categories: 45 documents were used to identify the factors of the environmental dimension, 33 for the factors of the economic dimension, 35 for the factors of the social dimension and 40 for the factors of the technological dimension.

After reading and analysing the 153 documents mentioned above, 32 indicators were obtained for the proposed dimensions of sustainability, of which 18 were related to environmental issues, four to social issues, four to economic aspects, and six to technological factors. Table 1 shows the 18 indicators selected for the environmental dimension, including “electricity use” and “transportation use”. For the economic dimension, the four selected indicators included “technological and/or sustainable investment” and “scrap recovery”. The four indicators for the social dimension included “staff training” and “collection of products”, and, finally, the six indicators of the technological dimension included “energy efficiency in product design” and “products that support maintenance”.

Table 1. Sustainability indicators for the manufacturing industry.

Dimension	Indicators	References
Environmental	Use of electricity	[17–31]
	Use of gas	
	Use of potable water	
	Quantity and type of waste generation	
	Recoverable waste	
	Greenhouse gas emissions	
	Electricity efficiency	
	Gas efficiency	
	Drinking water efficiency	
	Waste generation	
	Toxic waste generation	
	Toxic substances	
	Product life cycle	
	Prolongation of useful life of materials	
	Reduction of material use	
	Reduction of energy consumption	
	Recovery of obsolete products	
	Use of transportation	

Table 1. *Cont.*

Dimension	Indicators	References
Economic	Technological and/or sustainable investment	[27,28,31–41]
	Return on investment	
	Saving sustainable practices	
	Scrap recovery	
Social	Staff training	[20,23,24,28,42–50]
	Communication to employees	
	Sustainable certifications	
	Product harvesting	
Technological	Energy efficiency in product design	[20,22,24,31,50–57]
	Energy efficiency in production systems	
	Energy efficiency in transportation systems	
	Modular products	
	Products for repair, rework, and refurbishment	
	Products that support maintenance	

Determination of I4.0 levels

Having analysed the pillars of I4.0 and its tools, the levels of integration that could be associated with sustainable practices were determined. Level 1 indicates that the company does not consider the proposed parameter, which means that they do not carry out a specific action. At Level 2, the activity related to the parameter is measured manually. At Level 3, the activity related to the parameter is measured by obtaining data through sensors and/or electronic tools/equipment, which are then manually analysed. Finally, at Level 4, the activity related to the parameter is measured using sensors and/or electronic tools/equipment to generate information for analysis with I4.0 tools (Table 2).

Table 2. I4.0 levels and their descriptions.

Levels	Description
Level 1	Activity related to the parameter is not measured
Level 2	Activity related to the parameter is measured manually
Level 3	Parameter activity is measured based on data from sensors and/or electronic tools/devices, with manual analysis
Level 4	Activity related to the parameter is measured through sensors and/or electronic tools/devices that provide information, which is then automatically analysed by an I4.0 tool

Structure of the pilot version of TB

After identifying and selecting the sustainable practices (32 items) and the I4.0 levels, the pilot design of the toolbox integrated 32 sustainable practices that were measured at four levels of development. In Figure 1, the first box represents the sustainability indicators, and the boxes with numbers correspond to the levels of integration of the I4.0 tools described in Table 2. The data collected for the pilot design of the toolbox is based on sustainability parameters and has been assessed on the basis of four levels that indicate the status of the industry in relation to the I4.0 pillars.

The environmental dimension involves 18 measurable parameters, as follows:

Parameter 1: Electricity usage monitoring.
Parameter 2: Gas usage monitoring.
Parameter 3: Water usage monitoring.
Parameter 4: Generated waste monitoring.
Parameter 5: Recoverable waste monitoring.
Parameter 6: Reporting and control of hazardous gas emissions.
Parameter 7: Development of electrical efficiency practices.
Parameter 8: Development of gas efficiency practices.
Parameter 9: Development of electrical efficiency practices.
Parameter 10: Identification of the sources of waste generation.
Parameter 11: Knowledge of whether a process/service generates toxic waste.
Parameter 12: Elimination of the use of toxic substances from products.
Parameter 13: Evaluation of the product life cycle.
Parameter 14: Design of products that extend the useful life of materials.
Parameter 15: Design of products that reduce the use of materials.
Parameter 16: Design of products that reduce the use of energy.
Parameter 17: Design of products that incorporate material recovery.
Parameter 18: Transportation usage based on environmental decisions.

The economic dimension involves four measurable parameters, as follows:

Parameter 19: Performance of an analysis of sustainable practices.
Parameter 20: Performance of ROI control of each technology and sustainable practice implemented.
Parameter 21: Performance of an analysis of the savings produced by sustainable practices.
Parameter 22: Control of economic inputs from waste recovery or transformation.

The social dimension has four measurable parameters, as follows:

Parameter 23: Provision of employee training on sustainability issues (recycling, toxic waste, environmental stewardship).

Parameter 24: Communication of the company's environmental performance to employees.
Parameter 25: Knowledge of what percentage of customers are interested in sustainable certification.
Parameter 26: Coordination with the customer on the take-back of the product at the end of its life cycle.

The technological dimension consists of six measurable parameters:

Parameter 27: Use of energy-efficient systems in product design.
Parameter 28: Use of energy-efficient systems in production systems.
Parameter 29: Use of energy-efficient systems in transportation systems.
Parameter 30: Designs modular products.
Parameter 31: Designs products that facilitate rework and renovation.
Parameter 32: Designs products that support maintenance.

Expert validation for the toolbox

In order to ensure a scientifically rigorous evaluation, experts conducted a comprehensive analysis of the elements under study, applying objective criteria of clarity and relevance [58]. These criteria were based on the conceptual coherence and thematic relevance of each element within the research context. To support their judgements, the experts provided detailed comments illustrating the rationale behind their choices, thus providing a solid basis for subsequent review and decision-making. In this process, different courses of action were considered for each element evaluated: clarifying its meaning or purpose, eliminating it if was deemed redundant or irrelevant, or retaining it in the tool if it was deemed essential to achieving the research objectives.

This systematic and methodical approach ensured the quality and coherence of the measurement tool used. A representative example of this process is shown in Figure 2, which serves as a concrete model of how the evaluation criteria were applied, and the results obtained in the analysis of the study elements. As can be seen in Figure 2, in question 14 of the toolbox, the experts consider that the item is not clear (marked in blue) and the item requires a few modification (marked in yellow) in the clarity criterion, and in the relevance criterion the experts consider that the item is not clear, after that, the item is rewritten, without affecting the toolbox in any way.

SUSTAINABLE INDICATOR	APLICATION I4.0 LEVEL 0	APLICATION I4.0 LEVEL 1	APLICATION I4.0 LEVEL 2	APLICATION I4.0 LEVEL 3
I12. Base the use of transport and distribution logistics on environmental decisions	Does not base its decisions of transport and distribution logistics on environmental considerations	Based on data obtained manually, make decisions that optimize routes and modes of transportation	It has software that provides carbon footprint data that is fed into a digital database to make decisions that optimise routes and modes of transport	It has cloud-connected software that provides automatic information on the carbon footprint, which would facilitate decision-making to optimize routes and modes of transportation
CLARITY	(1) The item is not clear		(3) The item requires few modifications	
	(2) The item requires quite a few modifications		(4) The item is clear and adequate	
RELEVANCE	(1) The item is not clear		(3) The item is relatively important	
	(2) The item has some relevance, but it can be the subject of measurement by someone else		(4) This item is very relevant and should be added	
I13. Report and control of greenhouse gases emissions	Does not report or control	Manual reporting and control	Reporting and controlling using sensors with manual analysis	Sensor-based reporting and control with automatic cloud-based analytics
CLARITY	(1) The item is not clear		(3) The item requires few modifications	
	(2) The item requires quite a few modifications		(4) The item is clear and adequate	
RELEVANCE	(1) The item is not clear		(3) The item is relatively important	
	(2) The item has some relevance, but it can be the subject of measurement by someone else		(4) This item is very relevant and should be added	
I14. Use eco-labels if required by the product	Does not have an eco-label	The information generated by the eco-labels is entered into a manual database	Information generated by ecolabels is entered into a digital database	The cloud automatically generates an analysis of the products using the information generated by the eco-labels
CLARITY	(1) The item is not clear		(3) The item requires few modifications	
	(2) The item requires quite a few modifications		(4) The item is clear and adequate	
RELEVANCE	(1) The item is not clear		(3) The item is relatively important	
	(2) The item has some relevance, but it can be the subject of measurement by someone else		(4) This item is very relevant and should be added	

Figure 2. Example of the expert validation survey.

As recommended by Levy and Varela [58], an analysis of the mean values from the evaluations of these items was carried out, and those with values lower than 2.5 were eliminated; items with evaluations in the range 2.5–3.5 were discussed with the experts to decide whether they should be eliminated or modified; and items with evaluation scores larger than 3.5 were kept. Figure 3 shows that indicators 13 through 17, which belong to the environmental dimension, have mean scores of below 2.5 and are therefore candidates for elimination. The full results of this evaluation can be found in Appendix 1, which contains the full Sustainability Toolbox validation study. After this evaluation, and based on the expert opinion, it was recommended to analyze 13 items, which were modified and even moved to another sustainability dimension. The final version of the toolbox contained 29 items, distributed as follows: 14 items in the environmental dimension, 5 items in the economic dimension, 4 items in the social dimension and 6 items in the technological dimension.

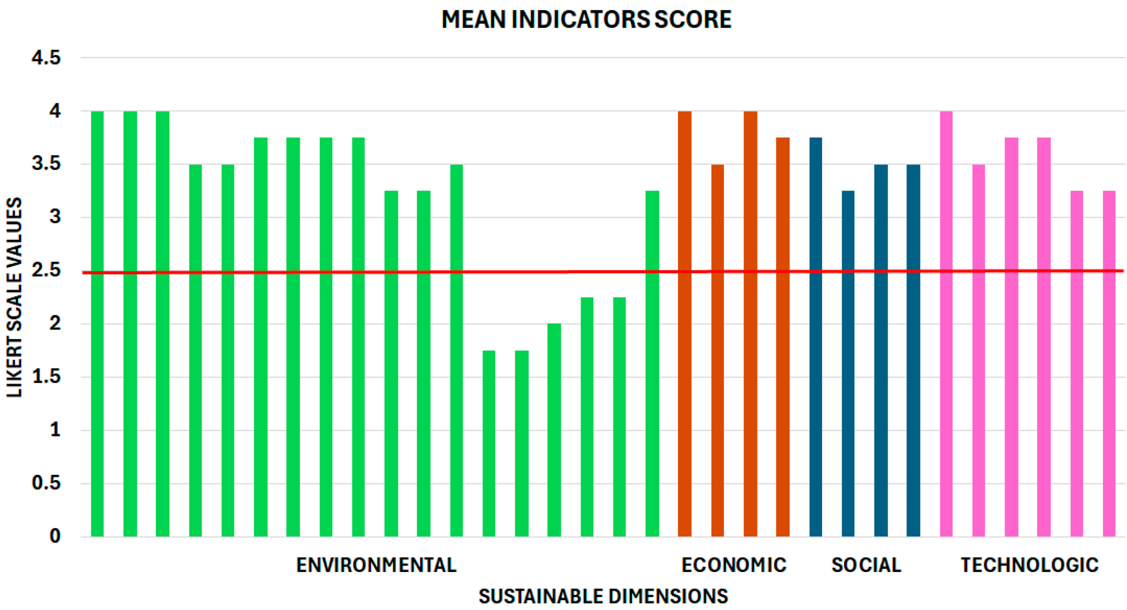

Figure 3. Graph of mean values for the selection of final indicators.

Image design for the toolbox

Adobe Illustrator was used to create images for the application interface, both for the sustainability indicators and for the proposed I4.0 levels. These images were generated exclusively for the development of the toolbox. An image was designed for each sustainability indicator and level of integration to the corresponding I4.0 tools, in order to ensure a visual representation of each answer option for a better understanding. The Sustainability Toolbox 4.0 is under review to be patented in Mexico as a sustainability evaluation system in the industry, which is why it is not fully included in this study. However, the parameters included here and used as basis for the diagnosis are those used in the toolbox.

Satisfaction survey

A questionnaire evaluating the usefulness of the toolbox was distributed to a sample of 105 people working in I4.0 manufacturing sectors in areas such as environment, finance, production, manufacturing, and technology.

Final version of the toolbox

The development of the S4.0 toolbox contain two sections: the first gathers information on the manufacturing company under evaluation, while the second contains 29 indicators with four graphic response options, these answers are related to the level of I4.0 that the company has. These indicators, which are divided into four dimensions of sustainability (environmental, economic, social, and technological), include energy efficiency, waste management, staff training in sustainable practices, investment returns for sustainable practices, and the manufacturing of modular products, among others. Appendices 2–6 contain the final version of the proposed S4.0 toolbox.

Sustainability 4.0 Diagnosis

As mentioned above, the second stage of the toolbox focuses on measuring S4.0 in industry to obtain a diagnosis of the level of integration of I4.0 pillars and sustainable practices.

Measurement in the field through the application of the toolbox

The questionnaire for diagnosis of S4.0 was distributed to subjects working in the manufacturing sector in different areas, such as aerospace, automotive, construction, electronics and communications, computer equipment and office accessories, transportation equipment, medical equipment, pharmaceuticals, integrators, electrical machinery, ferrous metals, non-ferrous metals, plastic and rubber, fabricated metal products, suppliers and chemicals. The companies were of different sizes (small, medium and large) and the specific areas of work included environmental, finance, production, manufacturing and technology. The surveys were administered physically.

Analysis of the satisfaction survey to assesses the usefulness of the toolbox

The survey was applied to 105 enterprises. The reliability of the data was estimated using the Cronbach's alpha value obtained, which is a measure used to determine the internal consistency of a test or scale [59]; its values range from 0 to 1. In this study the value obtained was 0.8188, indicating that the participants who completed the satisfaction survey understood the questions.

Diagnosis of S4.0

An analysis of the data showed that 90.48% of the respondents in the study were from large companies, and the remaining 9.52% were from medium, small, and micro enterprises (MSMEs). The large enterprises and MSMEs had levels of adoption of S4.0 of 3.11% and 0.34%, respectively.

The overall level of adoption of S4.0 in the manufacturing sector of Ciudad Juárez was 6.47%. This score was obtained by asking about the degree of integration of sustainable practices with I4.0, and the levels of adoption for each indicator and the sustainability dimensions (environment, economy, social, and technology) (Figure 4a,b,c,d). It is important to note that Level 4 indicators were considered.

Figure 4a shows the results for the activities associated with the environmental dimension that were carried out by manufacturing companies through the integration of I4.0 tools. Water consumption monitoring, recyclable waste monitoring, and a knowledge of the sources that generate waste were implemented by 9.52%, whereas monitoring of electrical energy consumption and basing logistics on environmental decisions were implemented by 8.57% of the companies. Reporting and control of greenhouse gas emissions were implemented by a total of 7.62%, and eliminating the use of toxic substances in products, monitoring waste generated and knowing whether their processes generate toxic waste were done by 6.67%. A total of 5.71% applied eco-labels to products that required them; 4.76% implemented water use efficiency practices; and 4.76% monitored natural gas usage. In addition, 3.81% implemented natural gas efficiency practices and 1.90% had electricity efficiency practices.

The results for the economic dimension are shown in Figure 4b. Control over the economic revenues from waste recovery was the most commonly introduced indicator for sustainability adoption, with the highest level of 9.52%, and this was followed by control over the return on investment for implemented technology sustainable practices, with a value of 4.76%. Lastly, the analysis of sustainable practices and the analysis of the savings they generate had an adoption rate of 3.81%. In regard to the social dimension, as shown in Figure 4c, the items with the highest level of integration of sustainability I4.0 were knowledge of whether customers are interested in sustainable certifications, and communication to personnel about environmental behaviour, with scores of 7.62%. Collection of the product at the end of its life cycle scored 6.67%, and finally, training personnel on sustainability issues scored 5.71%.

From an analysis of the data in Figure 4d, we see that the implementation of manufacturing products to support maintenance with I4.0 tools was done by 10.48% of the companies, while 7.62% were applying energy-efficient systems in the manufacturing of their products. A total of 5.71% were producing modular products and considering the use of energy efficiency systems in transport issues, while 4.76% were measuring production—remanufacturing and renovation and energy efficiency systems in production.

(**a**)

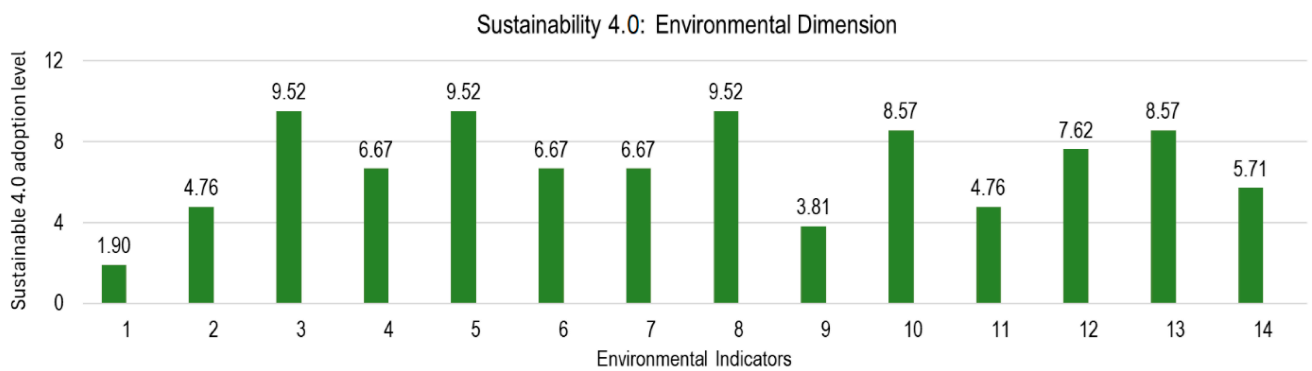

Figure 4. Level of adoption by indicator for the four dimensions of sustainability: (**a**) environmental, (**b**) economical, (**c**) social and (**d**) technological.

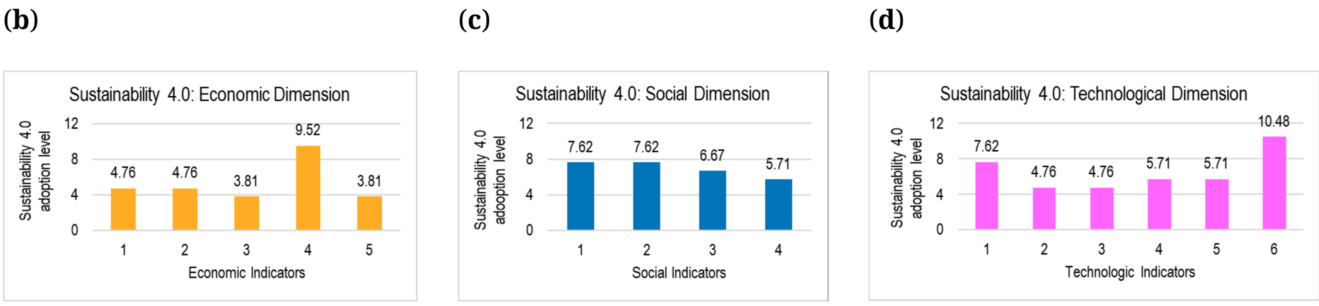

Figure 4. *Cont*.

DISCUSSION

The toolbox was developed to enable the evaluation of the level of adoption of sustainable practices and the use of tools of the pillars of I4.0 (S4.0), and to measure and monitoring factors such as the efficient use of resources. It offers an opportunity to easily determine the sustainable performance of industrial companies, in regard to the four dimensions that are linked to the productive processes of companies: environmental, economic, social, and technological. Each of these aspects has an influence on the value chain of the manufacturing industry. It should be noted that the interest in the development and adoption of sustainable practices and their integration with Industry 4.0 tools has increased significantly in recent years [60]. We can observe an increase in studies that report the indicators of these practices that are integrated into industrial processes to improve their performance in terms of the objectives of the sustainable development model [61,62]. This highlights the importance of the study, since in order to control the behavior and performance of a system that has an impact on the various development sectors, such as the economic, social and environmental, it is first necessary to measure that behaviour in order to identify in which practices or factors the standards proposed to reduce this impact are not being met. That is why we present the Sustainability 4.0 toolbox.

This study started with an analysis of the sustainable practices that can be implemented in industrial companies. Also focuses on these practices and combines them with I4.0 tools to create an evaluation tool to facilitate the measurement of the adoption of sustainability, taking advantage of the tools offered by the pillars of I4.0, this aims to reduce the impact of industrial practices and their contribution to climate change and to social and economic development at local, regional and national levels.

Our toolbox offers a simple way of evaluating and hence diagnosing the performance of companies in relation to the level of sustainability adoption, which can also be related to the effects of local and regional development. It represents a process allowing companies to determine the level of adoption of sustainability and to understand the effects they have, and specifically the activities that have this effect. A sustainability assessment is the first step to starting a transition towards the sustainable development model. Figure 5 shows the percentage of the total S4.0 in each of the sustainability dimensions that manufacturing companies in Ciudad Juárez have implemented. The environmental dimension is in first place at 6.90%, followed by the ecological dimension at 6.73%, the technological dimension at 6.51%, and the economic dimension at 5.33%. This clearly shows the need for a tool that facilitates the evaluation and quantitatively reports the performance in terms of the sustainability of manufacturing companies, since, as previously mentioned, this development sector has a significant impact [63].

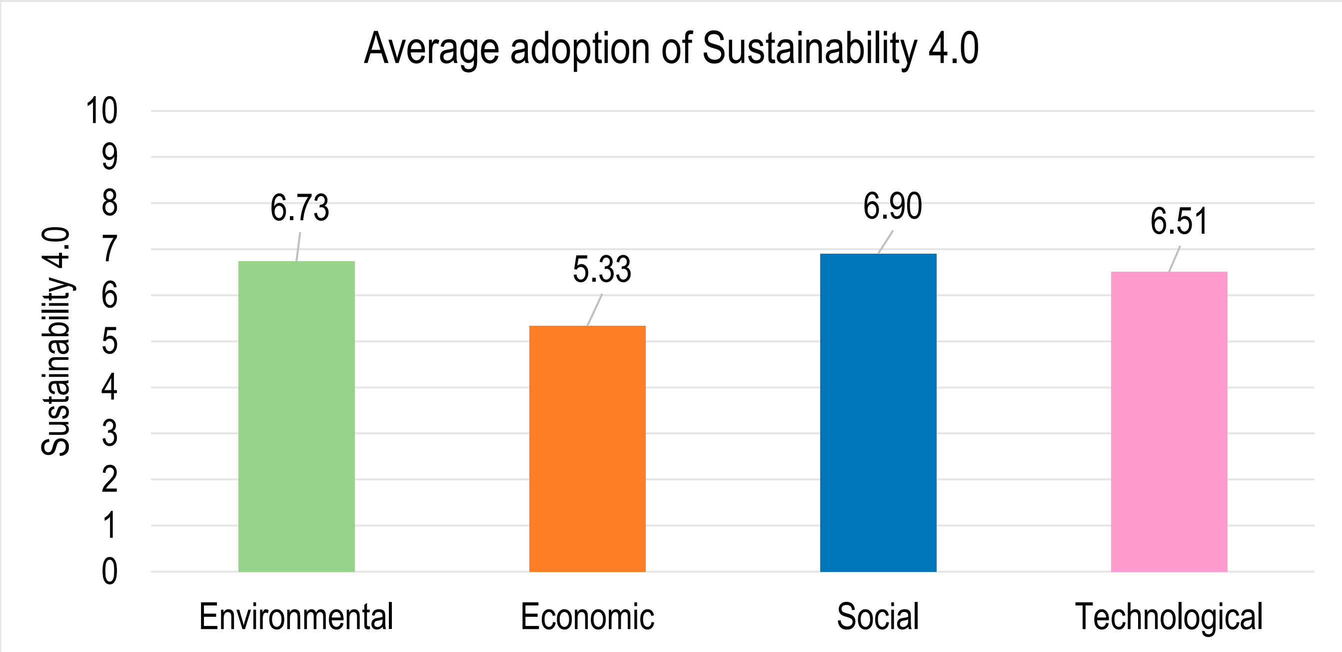

Figure 5. Percentage level of adoption of S4.0 by dimension.

As pointed out by Dreyer et al. [64], the evaluation of the social and environmental aspects, and in the case of the manufacturing industry, the economic and technological impacts, involves judgments based on a solid understanding of the methodological tools when considering the best practices related to these dimensions. Our toolbox may contribute to efforts to comply with international standards in all areas of development in relation to sustainability [49]. In this context, the proposed S4.0 toolbox represents a useful option for industrial enterprises.

CONCLUSION

The results presented here indicate that the proposed toolbox for measuring sustainability in the manufacturing industry is adequate for the diagnosis of the degree of implementation of S4.0 in the manufacturing industry of Ciudad Juárez. Our toolbox gives companies recommendations for the technologies they should adopt to become more competitive and socially responsible.

Our results show that MSMEs are still in the process of transitioning to sustainable process management by adopting the tools of Industry 4.0 technologies, which can contribute to the integration of smart production with the sustainable development paradigm, as proposed by [65].

Despite the capabilities they have, the level of integration of sustainable practices with I4.0 tools is only 3.1% for large companies. In this context, it would be wise to develop strategies as guides for the manufacturing sector to adopt sustainable practices in its four dimensions and integrate I4.0 tools. With the digitalisation of their processes, the adoption of sustainable practices will be easier and more viable, since their impact can be measured immediately and accurately.

It should be noted that the adoption of sustainability practices using the I4.0 tool, according to the dimensions considered here, takes greater account of social criteria and therefore has a higher level of integration due to the need to pay attention to employees. However, the economic aspect has the lowest level of adoption, and this is an area of opportunity, as businesses usually seek economic returns from their processes; they can apply strategies to automate their processes for benefits in economic terms and to improve their competitiveness.

This diagnosis enables us to see how industries have integrated and are integrating I4.0 practices. The results indicate a lack of knowledge of integration that would enable greater control of practices and help lead the industry not only towards the new industrial revolution but also towards a sustainable development model.

DATA AVAILABILITY

The dataset used for the study is available from the authors upon reasonable request.

AUTHOR CONTRIBUTIONS

Conceptualization, CA and VTA; Literature Review, CA; Investigation, CA and VTA; Development of Toolbox, CA and VTA; Field Measurement, CA; Supervision, VTA; Formal Analysis, VTA and SN; Writing—Original Draft, VTA; Review and Editing, SN. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest.

ACKNOWLEDGMENTS

The authors are grateful to the National Council for Science and Technology (CONAHCYT) for the main author's scholarship.

APPENDICES

Toolbox for Measuring the State of Sustainability in Industrial Plants Adopting Industry 4.0 (TB-S4.0)

Appendix 1. Expert validation for the toolbox.

SUSTAINABLE DIMENSION	ITEMS	EXPERT 1	EXPERT 2	EXPERT 3	EXPERT 4	MEAN	CRITERION
ENVIRONMENTAL	1	4	4	4	4	4	RETEIN
	2	4	4	4	4	4	RETEIN
	3	4	4	4	4	4	RETEIN
	4	4	2	4	4	3.5	ANALYZE
	5	4	2	4	4	3.5	ANALYZE
	6	3	4	4	4	3.75	RETEIN
	7	3	4	4	4	3.75	RETEIN
	8	3	4	4	4	3.75	RETEIN
	9	3	4	4	4	3.75	RETEIN
	10	3	4	3	3	3.25	ANALYZE
	11	3	4	3	3	3.25	ANALYZE
	12	3	4	3	4	3.5	ANALYZE
	13	1	2	2	2	1.75	DELETE
	14	1	4	1	1	1.75	DELETE
	15	2	3	2	1	2	DELETE
	16	2	2	2	3	2.25	DELETE
	17	2	2	3	2	2.25	DELETE
	18	3	4	3	3	3.25	ANALYZE
ECONOMIC	19	4	4	4	4	4	RETEIN
	20	4	2	4	4	3.5	ANALYZE
	21	4	4	4	4	4	RETEIN
	22	4	4	3	4	3.75	RETEIN
SOCIAL	23	4	4	3	4	3.75	RETEIN
	24	3	4	3	3	3.25	ANALYZE
	25	4	4	3	3	3.5	ANALYZE
	26	3	3	4	4	3.5	ANALYZE
TECHNOLOGIC	27	4	4	4	4	4	RETEIN
	28	4	4	4	2	3.5	ANALYZE
	29	4	4	4	3	3.75	RETEIN
	30	4	4	4	3	3.75	RETEIN
	31	3	4	3	3	3.25	ANALYZE
	32	3	4	3	3	3.25	ANALYZE

Appendix 2. Company Information.

1 Type of Industry
a) High Technology
b) Medium-High Technology
c) Medium-Low Technology
d) Low Technology
2 Industry size
a) Micro industry (1 to 10 employees)
b) Small industry (10 to 50 employees)
c) Medium industry (50 to 1000 employees)
d) Large industry (more than 1000 employees)
3. Geographic scope
a) Local
b) Regional
c) National
d) Continent
e) World
4 Who is primarily responsible for environmental issues?
a) Senior Management
b) Logistics Department
c) Environment Department
d) Marketing Department
e) Finance Department
f) Sales Department
g) Engineering Department
h) Health and Safety
5 Who is primarily responsible for technological issues?
a) Senior Management
b) Logistics Department
c) Environment Department
d) Marketing Department
e) Finance Department
f) Sales Department
g) Engineering Department
h) Health and Safety

Appendix 3. Environmental indicators.

ENVIRONMENTAL INDICATORS				
Sustainable Indicator	**I4.0 Adoption Level 1**	**I4.0 Adoption Level 2**	**I4.0 Adoption Level 3**	**I4.0 Adoption Level 4**
I1. Monitoring power consumption	No monitoring	Manual reporting monitoring	Sensor monitoring with manual analysis to plan and control processes	Sensor monitoring with automatic analysis in the cloud for planning and control
I2. Develop electrical efficiency practices	Does not develop electrical efficiency practices	Perform efficient practices through manual activities	Perform efficient semi-automated procedures	Perform efficient practices automatically thanks to the planning and control analysis generated in the cloud
I3. Monitoring natural gas consumption	No monitoring	Manual reporting monitoring	Sensor monitoring with manual analysis to plan and control processes	Sensor monitoring with automatic analysis in the cloud for planning and control
I4. Develop natural gas efficiency practices	Has no gas efficiency practice development	Perform efficient practices through manual activities	Perform efficient semi-automated procedures	Perform efficient practices automatically thanks to the planning and control analysis generated in the cloud
I5. Monitoring water consumption	No monitoring	Manual reporting monitoring	Sensor monitoring with manual analysis to plan and control processes	Sensor monitoring with automatic analysis in the cloud for planning and control
I6. Develop water efficiency practices	Does not develop water efficiency practices	Perform efficient practices through manual activities	Perform efficient semi-automated procedures	Perform efficient practices automatically thanks to the planning and control analysis generated in the cloud
I7. Monitoring of waste generation	No monitoring	Manual reporting monitoring	Sensor monitoring with manual analysis to plan and control processes	Sensor monitoring with automatic analysis in the cloud for planning and control
I8. Monitoring of recoverable residues	No monitoring	Manual reporting monitoring	Sensor monitoring with manual analysis to plan and control processes	Sensor monitoring with automatic analysis in the cloud for planning and control

Appendix 3. *Cont.*

ENVIRONMENTAL INDICATORS				
Sustainable Indicator	**I4.0 Adoption Level 1**	**I4.0 Adoption Level 2**	**I4.0 Adoption Level 3**	**I4.0 Adoption Level 4**
I9. Report and control of greenhouse gases emissions	Does not report or control	Manual reporting and control	Reporting and controlling using sensors with manual analysis	Sensor-based reporting and control with automatic cloud-based analytics
I10. Identify the source of waste generation	Does not identify the source of waste generation	Perform manual reviews	Identification by sensors with a manual report	Identify sensors with automatic cloud-based analysis to plan and control
I11. Know if the process generates toxic waste?	Do not know if the process/service generates toxic waste	Perform manual reviews	Identification by sensors with a manual report	Identify sensors with automatic cloud-based analysis to plan and control
I12. Eliminates the use of toxic substances in the products	No concern for the type of substances used	Performs manual identification of toxic substances	Design of products with data storage for autonomous exchange of information on toxic substances	Design products—with data storage for autonomous exchange of information on toxic substances—through 3D printing
I13. Base the use of transport and distribution logistics on environmental decisions	Does not base its decisions of transport and distribution logistics on environmental considerations	Based on data obtained manually, make decisions that optimize routes and modes of transportation	It has software that provides carbon footprint data that is fed into a digital database to make decisions that optimise routes and modes of transport	It has cloud-connected software that provides automatic information on the carbon footprint, which would facilitate decision-making to optimize routes and modes of transportation
I14. Use eco-labels if required by the product	Does not have an eco-label	The information generated by the eco-labels is entered into a manual database	Information generated by ecolabels is entered into a digital database	The cloud automatically generates an analysis of the products using the information generated by the eco–labels

Appendix 4. Economic indicators.

ECONOMIC INDICATORS				
Sustainable Indicator	**I4.0 Adoption Level 1**	**I4.0 Adoption Level 2**	**I4.0 Adoption Level 3**	**I4.0 Adoption Level 4**
I15. Conduct an analysis of sustainable practices	Does not perform an analysis of sustainable practices	Perform manual analysis on data from manual reporting	Perform manual analysis on data obtained from the digital database	The cloud automatically generates an analysis of sustainable practices
I16. Analyze savings from sustainable practices	Does not perform analysis of the savings produced	Perform manual analysis on data from manual reporting	Perform manual analysis on data obtained from the digital database	The cloud automatically generates an analysis of sustainable practices
I17. Perform return on investment control for each sustainable practices implemented	Does not perform investment control for each sustainable practices implemented	Perform manual investment control using data from manual reporting	Perform manual investment control with data obtained from the digital database	The Cloud Automatically Generates Investment Control
I18. Perform return on investment control for each technology practices implemented	Does not perform investment control for each technology practices implemented	Perform manual investment control using data from manual reporting	Perform manual investment control with data obtained from the digital database	The Cloud Automatically Generates Investment Control
I19. Perform economic inputs control for recovery or transformation waste	Does not perform economic inputs control for recovery or transformation waste	Perform manual economic inputs control using data from manual reporting	Perform manual economic inputs control with data obtained from the digital database	The Cloud Automatically Generates Economic Inputs Control

Appendix 5. Social indicators.

SOCIAL INDICATORS				
Sustainable Indicator	**I4.0 Adoption Level 1**	**I4.0 Adoption Level 2**	**I4.0 Adoption Level 3**	**I4.0 Adoption Level 4**
I20. Training staff on sustainability issues	Does not provide training to staff on sustainable issues	Provides training to staff supported by a paper manual that deals with sustainability issues in the industry	Provides training to staff supported by manuals generated in databases that deal with sustainability issues in the industry	Provides training to staff on sustainability issues in the industry, supported by I4.0 tools
I21.Communicating the company's environmental behavior to workers	Does not communicate the company's environmental performance to workers	Communicates the company's environmental performance to workers through manual reports	Communicates the company's environmental performance to workers through reports entered into a database	Communicates the company's environmental performance to workers through reports generated automatically in the cloud
I22. Know the percentage of your customers are interested in having sustainable certifications	Does not have any knowledge on the subject in question	Analyse customers interested in sustainable certification through manual reporting	Does has a digital database from which it manually filters clients interested in sustainable certification	The cloud automatically generates a report of customers interested in sustainable certification
I23. Coordinate with the client the collection of the product when it completes its life cycle	Does not coordinate with the client the collection of the product when it completes its life cycle	Maintains telephone/personal contact with the client to coordinate the collection of the product when it completes its life cycle	Supported by messages that are programmed according to the product's life cycle in which the client is informed to go to a collection center	Supported by RFID technology that generates data in the cloud, at the end of the product's life cycle, the client is automatically informed of the nearest collection centers

Appendix 6. Technologic indicators.

TECHNOLOGIC INDICATORS				
Sustainable Indicator	**I4.0 Adoption Level 1**	**I4.0 Adoption Level 2**	**I4.0 Adoption Level 3**	**I4.0 Adoption Level 4**
I24. Use energy efficiency systems in the manufacturing of products	Manufacturing products does not use energy efficiency systems	Implement energy efficiency practices through manual activities in manufacturing of products	Perform semi-automated energy efficient practices in manufacturing of products	Automatically implement energy efficiency practices in manufacturing products with cloud–generated planning and control analytics
I25. Use energy efficiency systems in production systems	Production systems do not use energy efficiency systems	Implementing energy efficiency practices through manual activities in production systems	Perform semi-automated energy efficient practices in production systems	Automatically implement energy efficiency practices in production systems with cloud-generated planning and control analytics
I26. Use energy efficiency systems in transportation systems	Transportation systems do not use energy efficiency systems	Implement energy efficiency practices through manual activities in transportation systems	Perform semi–automated energy efficient practices in transport systems	Automatically implement energy efficiency practices in transport systems with cloud–generated planning and control analytics
I27. Designs modular products	Does not design modular products	Design products based on manual identification of possible modular parts	Design products with data storage for autonomous exchange of information about possible modular parts	Design products—with data storage for autonomous exchange of information on possible modular parts—using 3D printing
I28. Design products that are easy to refurbish and renew	Does not design products that facilitate rework and renewal	Design products based on manual identification of possible parts that facilitate rework and renewal	Design products with data storage for autonomous exchange of information on possible parts that facilitate rework and renewal	Design products—with data storage for autonomous exchange of information on possible parts that facilitate rework and renewal—using 3D printing
I29. Designs products that support maintenance	Does not design products to support maintenance	Designs products based on manual identification of possible maintenance-supporting parts	Designs products with data storage for autonomous exchange of information about possible maintenance–supporting parts	Designs products—with data storage for autonomous exchange of information on possible maintenance—supporting parts—using 3D printing

REFERENCES

1. IPCC. Climate Change 2013. Available from: https://www.researchgate.net/profile/Abha_Chhabra2/publication/271702872_Carbon_and_Other_Biogeochemical_Cycles/links/54cf9ce80cf24601c094a45e/Carbon-and-Other-Biogeochemical-Cycles.pdf. Accessed on 22 Jan 2022.
2. Steffen W, Richardson K, Rockström J, Cornell SE, Fetzer I, Bennett EM, et al. Planetary boundaries: Guiding human development on a changing planet. Science. 2015;347(6223):1259855.
3. Brundtland GH. Informe de la Comisión Mundial sobre Medio Ambiente y el Desarrollo: Nuestro futuro común [Report of the World Commission on Environment and Development: Our common future]. Available from: https://www.ecominga.uqam.ca/PDF/BIBLIOGRAPHIE/GUIDE_LECTURE_1/CMMAD-Informe-Comision-Brundtland-sobre-Medio-Ambiente-Desarrollo.pdf. Accessed on 19 Nov 2024.
4. Utting P. Business responsibility for sustainable development. Geneva (Switzerland): United Nations Research Institute for Social Development; 2000.
5. Porter ME, Kramer MR. Creating shared value. Harv Bus Rev. 2011;89(12):1-17.
6. Lopes de Sousa Jabbour AB, Chiapetta Jabbour CJ, Foropon C, Godinho Filho M. When titans meet—Can industry 4.0 revolutionise the environmentally-sustainable manufacturing wave? The role of critical success factors. Technol Forecast Soc Change. 2018;132:18-25.
7. Román Del Val JL. La Digitalización y la Industria 4.0: Impacto industrial y laboral [Digitalization and Industry 4.0: Industrial and labor impact]. Available from: https://industria.ccoo.es/4290fc51a3697f785ba14fce86528e10000060.pdf. Accessed on 19 Nov 2024. Spanish.
8. Bonilla SH, Silva HRO, da Silva MT, Gonçalves RF, Sacomano JB. Industry 4.0 and sustainability implications: A scenario-based analysis of the impacts and challenges. Sustainability. 2018;10(10):3740.
9. Narwane VS, Raut RD, Yadav VS, Singh AR. Barriers in sustainable industry 4.0: A case study of the footwear industry. J Sustain Eng. 2021;14(3):175-89.
10. Argüelles C, Torres-Argüelles V. Caja de herramientas para la autoevaluación de la sustentabilidad en la Industria 4.0 [Toolbox for self-assessment of sustainability in Industry 4.0] [dissertation]. Ciudad Juárez (Mexico): Universidad Autónoma De Ciudad Juárez; 2019. Spanish.
11. Gobierno del Estado Libre y Soberano de Chihuahua. Programa sectorial Secretaría de Desarrollo Rural 2017-2021 [Sectoral program of the Secretariat for Rural Development 2017-2021]. Available from: http://ihacienda.chihuahua.gob.mx/tfiscal/indtfisc/progsec17/anexo065-2017rural.pdf. Accessed on 19 Nov 2024. Spanish.
12. Anderl R, Fleischer J. Guideline Industrie 4.0. Available from: https://www.pac.gr/bcm/uploads/guideline-industrie-4-0-vdma.pdf. Accessed on 11 Nov 2021.

13. Escobar-Pérez J, Cuervo-Martínez Á. Validez de contenido y juicio de expertos: Una aproximación a su utilización [Content validity and expert judgment: An approach to its use]. Advances Medición. 2008;6(1):27-36. Spanish.
14. Cabero J, Llorente M. La aplicación de juicio de experto como técnica de evaluación de las TIC [The application of expert judgment as an ICT evaluation technique]. Rev Eduweb. 2013;7(2):11-22. Spanish.
15. Namakforoosh MN. Metodología de la Investigación [Research Methodology]. 2nd ed. Mexico (Mexico): Editorial Limusa; 2000. Spanish.
16. Spooren P, Mortelmans D, Denekens J. Student evaluation of teaching quality in higher education: Development of an instrument based on 10 Likert-scales. Assess Eval High Educ. 2007;32(6):667-79.
17. Chen J, Cheng J, Dai S. Regional eco-innovation in China: An analysis of eco-innovation levels and influencing factors. J Clean Prod. 2017;153:1-14.
18. Chen W, Chen J, Xu D, Liu J, Niu N, Chen W, et al. Assessment of the practices and contributions of China's green industry to the socio-economic development. J Clean Prod. 2017;153:648-56.
19. Dörry S, Schulz C, Dörry S. Green financing, interrupted. Potential directions for sustainable finance in Luxembourg. Local Environ. 2018;23(7):717-33.
20. Wiloso EI, Nazir N, Hanafi J, Siregar K, Harsono SS. Life cycle assessment research and application in Indonesia. Int J Life Cycle Assess. 2018;24:386-96.
21. Nicholson SR, Nicholas A, Carpenter AC, Beckham GT. Manufacturing energy and greenhouse gas emissions associated with plastics consumption emissions associated with plastics consumption. Joule. 2020;5(3):673-86.
22. Ayvaz B, Kusakci AO, Aydın N, Ertaş E. Designing reverse logistics network for end-of-life vehicles: a sustainability perspective in a fragile supply chain. Int J Ind Eng Theory. 2021;28(3):298-328.
23. Ferreira J. Industry 4.0 implementation: Environmental and social sustainability in manufacturing multinational enterprises. J Clean Prod. 2023;404:136841.
24. Kao HY, Lan ZH, Huang CH, Huang CH. A two-stage bi-level decision approach for green supply chain design and cloud virtual machine placement. Int J Ind Eng Theory. 2022;28(5):529.
25. Ma S, Ding W, Liu Y, Ren S, Yang H. Digital twin and big data-driven sustainable smart manufacturing based on information management systems for energy-intensive industries. Appl Energy. 2022;326:119986.
26. Atagamen P, Eghonghon K, Edetalehn I, Frederick B, Eshioke P, Olaleye B, et al. Heliyon Bioenergy revamping and complimenting the global environmental legal framework on the reduction of waste materials: A facile review. Heliyon. 2023;9(1):e12860.
27. Das S, Fuchs H, Philip R, Rao P. A review of water valuation metrics: Supporting sustainable water. Water Resour Ind. 2023;29:100199.
28. Sadchenko O, Obykhod H, Yaroshenko I, Levkovska L, Deineha O, Dombrovska T. Management of the economy in the field of environmental management and energy security as components of sustainable development. J Sustain Res. 2022;4(2):e220008.

29. Debnath B, Bari ABMM, Mithun S, Ahmed T, Ali I. Modelling the barriers to sustainable waste management in the plastic-manufacturing industry: An emerging economy perspective. Sustain Anal Model. 2023;3:100017.
30. Ibn Batouta K, Aouhassi S, Mansouri K. Energy efficiency in the manufacturing industry—A tertiary review and a conceptual knowledge-based framework. Energy Rep. 2023;9:4635-53.
31. Nunez Madrigal A, Iyer-Raniga U, Yang RJ. Exploring PV waste management solutions using circular strategies. J Sustain Res. 2023;5(2):e230008.
32. Bak C, Bhattacharya A, Edenhofer O, Knopf B. Towards a comprehensive approach to climate policy, sustainable infrastructure, and finance. Economics. 2017;11(1):20170033.
33. Falcone PM, Morone P, Sica E. Greening of the financial system and fuelling a sustainability transition: A discursive approach to assess landscape pressures on the Italian financial system. Technol Forecast Soc Change. 2018;127:23-37.
34. Liyanaarachchi N, Rupasinghe TD. An analytical modelling approach to assess the applicability of green chain operations: A case study from the Sri Lankan apparel industry. Available from: http://tiikmpublishing.com/data/conferences/doi/wcosm/wcosm.2017.2101.pdf. Accessed on 19 Nov 2024.
35. Couto G, Jordan M, Capaldo D. The industrial symbiosis in the product development: An approach the Conference Costing models for capacity optimization in Industry 4 .0: Trade-off. Procedia Manuf. 2018;21:862-9.
36. Han R. Research on the industrial foundation and financial support of green economy development. Open Access Libr J. 2018;5:e4873.
37. Mohd S, Kaushal VK. Green finance: a step towards sustainable development. MUDRA J Financ Account. 2018;5(1):59-74.
38. de Oliveira UR, Espindola LS, da Silva IR, da Silva IN, Rocha HM. A systematic literature review on green supply chain management: research implications and future perspectives. J Clean Prod. 2018;187:537-61.
39. Bhattacharya A. Achieving sustainability in supply chain operations in the interplay between circular economy and Industry 4.0. Prod Plan Control. 2023;34(10):867-9.
40. Saraswathi S, Deepa G, Vennila G, Parthasarathy S, Ramadoss B. A survey on big data: Infrastructure, analytics, visualization and applications. Int J Ind Eng Theory. 2022;29(5):618.
41. Ma S, Huang Y, Liu Y, Kong X, Yin L. Edge-cloud cooperation-driven smart and sustainable production for energy-intensive manufacturing industries. Appl Energy. 2023;337:120843.
42. Herczeg G, Akkerman R, Hauschild MZ. Supply chain collaboration in industrial symbiosis networks. J Clean Prod. 2018;171(10):1058-67.
43. Na-nan K, Kanthong S, Joungtrakul J. An empirical study on the model of self-efficacy and organizational citizenship behavior transmitted through employee engagement, organizational commitment and job satisfaction in the Thai automobile parts manufacturing industry. J Open Innov Technol Mark Complex. 2021;7(3):170.

44. Abdallah KS, El-Beheiry MM. A system dynamics model assessing the sustainability of the performance of supply chains with reverse flow. Int J Ind Eng Theory. 2022;29(4):562.
45. Amend C, Revellio F, Tenner I, Schaltegger S. The potential of modular product design on repair behavior and user experience—Evidence from the smartphone industry. J Clean Prod. 2022;367:132770.
46. Menon RR, Ravi V. Using AHP-TOPSIS methodologies in the selection of sustainable suppliers in an electronics supply chain. Clean Mater. 2022;5:100130.
47. Gungor C. Safety sign comprehension of fiberboard industry employees. Heliyon. 2023;9(6):e16744.
48. Ololade AJ, Paul SO, Morenike AT. Bolstering the role of human resource information system on employees' behavioural outcomes of selected manufacturing firms in Nigeria. Heliyon. 2023;9(1):e12785.
49. Squier H, Booth C. Insights from the analysis of sustainability reporting across UK real estate companies. J Sustain Res. 2023;5(2):e230005.
50. Jelena KP. On remanufacturing readiness level—An introduction to a Remometer™. Procedia CIRP. 2021;98:91-6.
51. Dahmani A, Benyoucef L, Mercantini J. Toward sustainable reconfigurable manufacturing systems (SRMS): Past, present, and future. Procedia Comput Sci. 2022;200:1605-14.
52. Shahzad M, Qu Y, Rehman SU, Zafar AU. Adoption of green innovation technology to accelerate sustainable development among manufacturing industry. J Innov Knowl. 2022;7(4):100231.
53. Turner C, Okorie O, Emmanouilidis C, Oyekan J. Circular production and maintenance of automotive parts: An Internet of Things (IoT) data framework and practice review. Comput Ind. 2022;136:103593.
54. Gao J, Feng Q, Guan T, Zhang W. Unlocking paths for transforming green technological innovation in manufacturing industries. J Innov Knowl. 2023;8(3):100394.
55. Li H, Hao Y, Xie C, Han Y, Wang Z. Emerging technologies and policies for carbon–neutral. Int J Transp Sci Technol. 2023;12(1):329-34.
56. Reaney IM, Walsh B, Vilarinho PM. Resource efficiency and energy efficiency (REEE) in the Portuguese ceramic industry: Towards net zero carbon production. Open Ceram. 2023;15:100390.
57. Shen Y, Zhang X. Intelligent manufacturing, green technological innovation and environmental pollution. J Innov Knowl. 2023;8(3):100384.
58. Lévy JP. Modelización y análisis con ecuaciones estructurales [Modeling and analysis with structural equations]. In: Lévy JP, Varela J, editores. Análisis Multivariante para las Ciencias Sociales [Multivariate Analysis for Social Sciences]. Madrid (Spain): Prentice Hall; 2003. p. 769-810. Spanish.
59. Tavakol M, Dennick R. Making sense of Cronbach's alpha. Int J Med Educ. 2011;2:53-5.
60. Fawzy S. Osman AI, Doran J, Rooney DW. Strategies for mitigation of climate change: A review. Environ Chem Lett. 2020;18:2069-94.

61. Gupta H, Kumar A, Wasan P. Industry 4.0, cleaner production and circular economy: An integrative framework for evaluating ethical and sustainable business performance of manufacturing organizations. J Clean Prod. 2021;295:126253.
62. Malesios C, De D, Moursellas A, Dey PK, Evangelinos K. Sustainability performance analysis of small and medium sized enterprises: Criteria, methods and framework. Socio-Econ Plan Sci. 2021;75:100993.
63. Mokbel Al Koliby IS, Abdullah HH, Mohd Suki N. Linking entrepreneurial competencies, innovation and sustainable performance of manufacturing SMEs. Asia Pac J Bus Adm. 2024;16(1):21-40.
64. Dreyer LC, Hauschild MZ, Schierbeck J. Characterisation of social impacts in LCA: Part 1: Development of indicators for labour rights. Int J Life Cycle Assess. 2010;15:247-59.
65. Gajdzik B. Grabowska S. Saniuk S. Wieczorek T. Sustainable development and industry 4.0: A bibliometric analysis identifying key scientific problems of the sustainable industry 4.0. Energies. 2020;13(16):4254.

How to cite this article:
Arguelles C, Torres-Arguelles V, Noriega S. Application of Toolbox Diagnosis of Sustainability 4.0 in Manufacturing Operations: Sustainability Integration in the Context of Industry 4.0. J Sustain Res. 2024;6(4):e240076. https://doi.org/10.20900/jsr20240076