sustainability

Article

Holistic Framework to Data-Driven Sustainability Assessment

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Abstract: In recent years, the Twin-Transition reference model has gained notoriety as one of the key options for decarbonizing the economy while adopting more sustainable models leveraged by the Industry 4.0 paradigm. In this regard, one of the most relevant challenges is the integration of data-driven approaches with sustainability assessment approaches, since overcoming this challenge will foster more agile sustainable development. Without disregarding the effort of academics and practitioners in the development of sustainability assessment approaches, the authors consider the need for holistic frameworks that also encourage continuous improvement in sustainable development. The main objective of this research is to propose a holistic framework that supports companies to assess sustainability performance effectively and more easily, supported by digital capabilities and data-driven concepts, while integrating improvement procedures and methodologies. To achieve this objective, the research is based on the analysis of published approaches, with special emphasis on the data-driven concepts supporting sustainability assessment and Lean Thinking methods. From these results, we identified and extracted the metrics, scopes, boundaries, and kinds of output for decision-making. A new holistic framework is described, and we have included a guide with the steps necessary for its adoption in a given company, thus helping to enhance sustainability while using data availability and data-analytics tools.

Keywords: Industry 4.0; decarbonizing; data-driven sustainability; holistic framework; continuous improvement; sustainability assessment; lean thinking; data analytics

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1. Introduction

Sustainable manufacturing is presently a top priority for governments and businesses all around the world [1]. Due to dwindling non-renewable resources, tougher environmental and occupational safety requirements, and rising customer desires for ecologically friendly products, achieving sustainability in industrial operations has been identified as a crucial necessity. The term sustainability encompasses three dimensions and works on delivering the performance result based on the triple bottom line (TBL) concept, first coined by John Elkington [2,3]. It is based on three fundamental dimensions: (i) economic challenges, by producing wealth and new services while ensuring long-term development and competitiveness; (ii) environmental challenges, by promoting the minimal use of natural resources (particularly non-renewable) and managing them in the best possible way while minimizing environmental impact; (iii) social challenges, considering the employees' working conditions and making their working environment comfortable [4]. The corporate development process can be allied with the TBL conceptualization, providing businesses with a better monetary outcome without compromising the environmental and social benefits; this is a fundamental requirement for companies to increase their competency in the market, and their economic outcome without compromising environmental and social benefits [5–7]. This need for sustainable development pushes companies to adapt the best sustainability assessment method that helps them to identify the current state of the company and to find areas that need improvement.

In light of this, several publications present approaches to measuring and quantifying the impacts of a company's actions on its sustainability performance, aiming to understand the result of each action at economic, environmental, and social levels [4]. Nevertheless, these approaches are case- or sector-specific, and do not comprise strategies for a high volume of data acquisition and treatment [4,8,9], resulting in a lack of standardization and comprehensiveness in the existing approaches [8]. Therefore, the companies lack an approach that allows for learning and understanding the impact of the actions taken at the three sustainability levels, preventing an effective and continuous increase in sustainability performance.

To cover this gap, a question can be raised: What are the requirements of a holistic framework for sustainability assessment that analyzes the current state of sustainability performance and encourages a continuous improvement culture? To fulfil the standardization issues identified, this framework must be comprehensive, based on quantitative performance assessment, and provide the opportunity to upgrade itself for future conditions. Therefore, the main contribution of this paper is to propose a holistic framework that will facilitate companies and businesses to assess sustainability performance effectively and effortlessly. To this effect, the paper analyzes several methodologies in which the main function consists of assessing the company's sustainability through a set of metrics that enable the conclusion of the company's status. After reviewing multiple approaches, it has been identified that data play a vital role in deciding the assessment results, hence data-driven sustainability assessment stands out of the crowd. Consequently, another contribution of this study is to nurture the holistic sustainability assessment framework with the steps necessary to implement a data-driven sustainability assessment, firstly as a way to assure performance tracking and improvement, and secondly as a basic requirement for the future application of complex data analytics models to the high volume of data available.

2. Literature Review on Sustainability Assessments

The base of the research was built by reviewing multiple sustainability assessment approaches. By doing so, the fundamental factors that are required to execute the assessment are addressed. Sustainability assessment approaches and data-driven sustainability assessment-related publications were searched in the databases "Google Scholar", "Research Gate", "Scopus" and "Springer", searching for Title, Abstract and Keywords. The following strings were used: "Sustainability Assessment", "Data-driven Sustainability Assessment", "Sustainability Assessment", "Data-driven", "Sustainability Assessment" and "Industry 4.0". More than 2000 articles were identified. The search was refined to select those that propose an approach, a framework or a method, resulting in 150+ publications. Among these, a detailed review was performed, selecting the ones presenting a sequential and applicable approach/methodology, based on industrial data-driven metrics and indicators, and/or a quantitative assessment outcome; a set of 28 publications was selected.

2.1. Need for Sustainability Assessment

John Elkington [2,3] coined TBL more than two decades ago, and recently concluded that the TBL concept has been captured and diluted by accountants and reporting consultants who use it as an accounting tool in a balancing act, and that it is far from clear that the resulting data are being aggregated and analyzed in ways that genuinely help decision-makers and policymakers to track, understand, and manage the systemic effects of human activity. John Elkington [2] proposed that businesses seek being not just the "best in the world," but the "best for the world". For this, we must work toward a triple helix in value creation, spurring the regeneration of our economies, societies, and biosphere [2].

To overcome these challenges, organizations must seek ways to assess their sustainability. It should be noted that this concept extends beyond the environmental dimension and is also characterized by its economic and social components [10,11]. At the economic level, it is necessary to analyze the aspects that contribute to keeping an organization competitive over the years, and thus encompass a set of measures to assess the creation of value for a company and its respective stakeholders. Concerning the social dimension, it is necessary to relate the impacts of an organization on the social system in which it is inserted, which covers the groups affected by the organization, such as relevant stakeholders. Lastly, the environmental dimension consists of ensuring the sustainability of the ecosystem, managing environmental impacts, and reducing resource consumption in production processes.

Currently, the theme of sustainability is becoming increasingly pressing, being necessary to provide the business and industrial sectors with tools that help offer a balance between pillars economic, social, and environmental. In addition, the development of products with better environmental performance is increasingly becoming a key process in companies in terms of the scope of sustainable development. As organizations face the problem of scarce resources, with the regulation of production becoming increasingly tight and the demand for sustainable products increasing, manufacturing companies have sought to respond to these needs through sustainable production. Thus, companies must evaluate their performance against achieving sustainable development to ensure that business consumption does not exceed the available resources of the planet [4,12].

Sustainability assessment is defined, by some authors, as any process that aims to contribute to a better understanding of the meaning of sustainability and its contextual interpretation. Following the same author, the three challenges of sustainability are interpretation, the structuring of information, and influence [8]. Thus, it is necessary to measure and quantify the impacts of a company's actions on its sustainability in order to understand the result of each action at economic, environmental, and social levels [4]. Despite several methods existing to address sustainability assessment, the lack of standardization in the assessment approach leads to a lack of greater focus in the approach [8]. This absence causes a failure in tracking problems and improvements, as well as their impacts on the company's sustainability, preventing the passage of knowledge from past events into the future [12].

2.2. Sustainability Assessment Approaches

In the publications analyzed in this study, there are multiple different data collection methods and tools used to assess sustainability from a triple-bottom line conceptualization. Singh et al. [9], Ghadimi et al. [13] and Amrina et al. [4] have used fuzzy logic to increase the reliability of the performance result. Kluczek [14], Harik et al. [6] and Shuaib et al. [15] have used a mathematical model to recognise the interdependencies and trade-offs between metrics. Armstrong et al. [12] and Eastwood and Haapala [10] have used a unit process model to break the general overview into multiple subcategories for a more effective result. Standard tools in the realm of life cycle and value analysis, such as Value Stream Mapping (VSM), Life Cycle Assessment (LCA), Life Cycle Sustainability Assessment (LCSA) and Social Life Cycle Assessment (S-LCA) have been used by several authors to assure a life cycle perspective in the assessment [7,14,15]. Additionally, standard methods of the decision theory body of knowledge, such as Analytic Hierarchy Process (AHP), multi-criteria decision making (MCDM) and fuzzy logic-based methods, were used, aiming to contribute to the selection and improvement of the most impactful indicators and parameters [4,6,9,13,14]. On one hand, despite the varied methods, the use of metrics and indicators to declare the performance result remains common. On the other hand, the scope of the assessment varies in terms of the product, company, and process, whereas certain authors extend their limit from cradle to cradle, while some only use a gate-to-gate approach.

A total number of 28 research articles, in which the environmental, social, and economic dimensions of sustainability are assessed from a holistic perspective, are represented in Table 1. For each of the references analyzed, the basic methodology, scope, quantity and types of indicators/metrics used by the authors, a brief description of the approach, and the final product (e.g., tables of final scores for sustainability) are indicated.

From the reviewed 28 approaches, the role of metrics/indicators and the requirement of data are crucial to interpreting the result of sustainability performance. The authors have used either subjective (surveys, interviews, etc.) [11,14] or objective data (operational data, product life cycle data, etc.) [4,16,17] to calculate the results of indicators. Subjective data are more dependent on humans, wherein the result is influenced by the concerns and perceptions of human beings, whereas objective data are measurable data represented with a fact or proof to declare the result. It is important to understand the context and use the relevant data type appropriately. The required data for sustainability assessment can be categorized based on the TBL conceptualization, into economic, environmental, and social data. Several authors state that a data-driven approach leverages digital technologies, where sustainability factors are extracted directly from the operational system when needed and processed automatically [13,18–21]. Those authors refer to a set of ground reasons to foster the extraction of the maximum benefits from data, which are: (i) To improve sustainability, there is the need to measure it using a reliable source; higher sustainability may be attained with a well-informed and organized data-collecting and analysis approach [19,20]. (ii) Insights from data should drive the strategy and should assist organizations in continuously improving [21]. (iii) Sustainability reporting requires accountable KPIs to facilitate root cause analysis [18,21]. (iv) Net zero targets are unattainable without effective monitoring [13,18].

Table 1. Sustainability assessment approaches.

Nº	Scope	Methodology	Indicators and Metrics	Outcome	Refs
1	Company	Based on fuzzy logic and specialists	Five metrics are considered for the environmental dimension, three for the social dimension and four for the economic dimension, covering all three dimensions of sustainability.	Sustainability assessment questionnaire	[9]
2	Product	Weighted Fuzzy Logic (WFAM)	The indicators cover the three dimensions of sustainability and are divided into a hierarchical structure of 4 levels: level 0—overall index; level 1—elements (Ex environmental); level 2—sub-elements (Ex greenhouse effect); level 4—influencing factors (e.g., carbon dioxide emissions).	Table with scores for each level of indicators except for influence factors	[13]
3	Company	Fuzzy multiple criteria methodology	Thirteen sustainability metrics are used, divided by the environmental (4), social (4) and economic (5) dimensions.	Final sustainability score	[4]
4	Process	Multi-criteria approach based on AHP	The environmental social, economic and technical dimensions of sustainability are considered. Twelve environmental metrics are used; however, it is not clear which metrics are used for the remaining dimensions.	Sustainability performance table with values for each step and scores	[14]
5	Company	Holistic sustainability index based on the AHP method	In total, 14 social indicators, 10 economic indicators, 13 environmental indicators and 7 production indicators are used to characterize the sustainability of an industry. These indicators characterize sub-indices that in turn determine an overall index.	Scoring of the sub-indices and the global sustainability index, allowing comparison between companies	[6]

Table 1. *Cont.*

Nº	Scope	Methodology	Indicators and Metrics	Outcome	Refs
6	Product	Based on LCA and LCC tools and metrics for assessing technical and social	There is no evidence of great comprehensiveness in the sustainability metrics. Seven indicators were chosen, divided into the technical (1), environmental (2), social (2) and economic (2).	Comparison between metrics from LCA, LCC, the social assessment and the technical assessment	[22]
7	Product	Combining the AHP method with LCSA	The environmental component includes 12 indicators, mostly quantitative, 5 social indicators and 1 economic indicator. They are hierarchical, corresponding to the building's overall sustainability.	Comparative table of total sustainability indexes	[23]
8	Company	Indicator-based rapid assessment tool	The authors refer to the use of 133 indicators divided into 7 management areas, without specifying them.	Sustainability assessment questionnaire	[11]
9	Work cell	Based on the combination of AHP and MCDM with LCA, SLCA, and cost analysis	We use 17 environmental impact metrics obtained through ReCiPe, 3 social impact metrics and the total cost for the economic aspect.	Table with a ranking for production alternatives, with a sensitivity analysis being carried out	[24]
10	Product	Based on LCA, LCC and injury risk analysis tools	Six environmental metrics and one economic (cost) metric were chosen.	Comparison between the results of the sustainability analysis for differentproductions	[12]
11	Product	Based on metrics organized hierarchically with an indexglobal (ProdSI)	The metrics are divided by a 5-level hierarchical structure: an overall aggregate index (ProdSI), 3 sub-indices (environmental social and economic), 13 clusters (Exo waste and emissions), 45 sub-clusters (Exo gaseous emissions) and 45 individual metrics (Exo greenhouse gases).	Comparing metrics for two generations of products through bar charts and spider graphs	[15]
12	Process	Based on metrics organized hierarchically with an indexglobal	The metrics are divided by a 5-level hierarchical structure: an overall aggregate index, named ProcSI, 6 clusters (Exo environmental impact), 25 sub-clusters (Exo water) and 89 individual metrics (Exo total water consumption).	Summary table for comparison between metrics for various machine operating parameters	[18]
13	Company	Based on metrics organised hierarchically with an indexglobal	The metrics are divided by a 5-level hierarchical structure: one overall aggregate index, 3 sub-indices (environmental social and economic), 9 clusters (Exo net profit), 22 sub-clusters (e.g., profit from operations) and 49 individual metrics (e.g., material costs).	Comparison of metrics obtained in certain years of activity	[25]
14	Production line	Value Stream Mapping with sustainability indicators, named Sus-VSM	For the environmental dimension, 3 metrics related to water, materials and energy consumption are considered. The consumption of materials is related to the economic component. For the social dimension, we consider metrics related to physical work and the dangers existing in the working environment.	VSM with the addition of water, material and energy consumption indicators and social indicators (risk)	[26]
15	Production line	Value Stream Mapping with indicators of sustainability	In total, 4 environmental metrics, 4 economic metrics and 4 social metrics are considered to assess sustainability.	VSM with the addition of environmental, economic and social metrics	[17]

Table 1. *Cont.*

Nº	Scope	Methodology	Indicators and Metrics	Outcome	Refs
16	Process	Unit Process Model with supporting software	Eight metrics were selected to assess environmental, social and economic aspects of sustainability.	Supporting IT tool with metrics results table and a radar chart	[12,19]
17	Process	Unit Process Model	In total, 1 economic performance metric, 7 environmental performance metrics and 3 social performance metrics were selected.	Table with metric results for 3 design alternatives of a component	[10]
18	Process	Fuzzy logic combined with the AHP method	The indicators cover the three dimensions of sustainability and are divided into a hierarchical structure of 4 levels: level 0—overall index; level 1—elements (Ex environmental); level 2—sub-elements (Ex emissions); level 4—influencing factors (e.g., carbon dioxide).	Table of environmental, social, economic and total sustainability scores for 4process alternatives	[27]
19	Product	Combining the AHP method with LCSA	The authors do not clearly express the indicators relevant to the study.	Table with ranking among waste disposal alternatives	[16]
20	Product	Based on LCSA (LCA, SLCA, LCC)	In total, 18 environmental impact metrics obtained through ReCiPe are used. Consumer and manufacturer costs are considered. Social impacts are analyzed qualitatively through 9 indicators.	Comparison of metrics obtained from assessment tools	[28]
21	Product	Integrated modelling and simulation	In total, 7 environmental metrics, 7 economic metrics and 6 social metrics are considered.	Results of sustainability assessment and simulation	[29]
22	Industry	System Thinking	In total, 25 environmental metrics, 20 economic metrics and 15 social metrics are considered.	Sustainability index	[30]
23	Company	System dynamics	In total, 11 environmental metrics, 10 economic metrics and 9 social metrics are considered.	Complete stock and flow model and metrics	[31]
24	Company	Design for sustainable manufacturing enterprise	Metrics covering several global aspects are used, but the use of environmental and social metrics is not clear.	Sustainability index	[7]
25	Company	Graph theory-based modelling	It considers 5 business metrics, 6 environmental metrics, 4 economic metrics and 5 social metrics.	Scorecards for best and worst cases	[32]
26	Product	Based on LCSA	As this is a general approach, environmental and economic sustainability metrics are not indicated. However, social indicators are provided.	Sustainability indices	[33]
27	Technologies	Based on the extended LCA	As this is a general approach, no sustainability metrics are indicated.	Impact display	[34]
28	Process	LCSA-based method	In total, 6 metrics relating to technology, 13 environmental metrics, 13 economic metrics and 5 social metrics are used.	Metrics for each alternative with colors representing the range to the benchmark	[35]

Figure 1 represents a simplified view of 28 assessment approaches, where the commonality is the wide variety of approaches and assessment outputs. Most of the publications (17 out of 28) use mathematical models from the realm of decision theory of the body of knowledge to deal with direct data or information from the processes and from the people involved, involving analyses of products, technologies, processes and even an entire company or industrial sector. The outputs of these approaches range from questionnaires to expert opinions, to sustainability indexes and scores for specific indicators. This wide variety is also found in the four approaches that integrate decision-making-based mathematical models with life cycle based or sustainability assessment methods. The remaining seven approaches use solely sustainability assessment methods, life cycle-based, or value flow analysis to assess the triple-bottom line performance, using those methods as the output of the analysis. These latter two types of publication focus only on narrowed objects of assessment, such as production lines, work cells, processes and products.

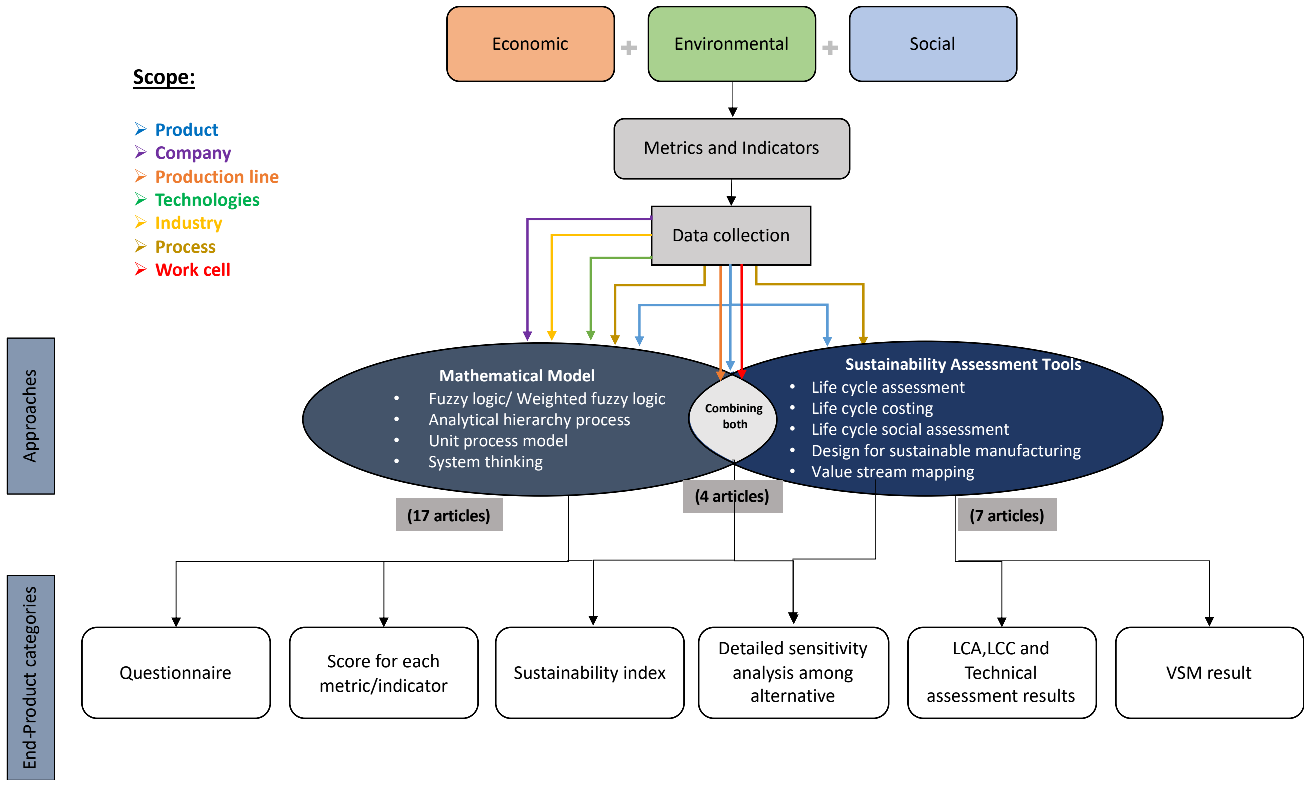

Figure 1. Overview of 28 sustainability assessment approaches.

Even though every approach has its own individuality, there are certain common elements that can be found in almost all of them, acting as prerequisites to fulfil the goals of an approach, and these are used in this study to understand the several existing contributions: (i) the goal/scope of the assessment; (ii) relevant indicators and metrics, and (iii) subjective/objective data; (iv) the relation between indicators; (v) assigning weights for indicators. In Table 2 and in the following paragraphs, an analysis of the surveyed literature regarding these five aspects is performed, aiming at depicting the already existing knowledge regarding sustainability assessments with special emphasis on the way the industrial and processes data are used and treated.

Table 2. Summarizing different approaches.

Requirements	Explanation	Refs
Goal/Scope	To define the goal and area of scope that needs to be assessed	[7,10–15,23,27,29,30,35]
Indicators	To identify the indicators that can help to convert the current scenario into a quantifiable value	[4,6,7,9–12,14–17,22,23,25–27,29–31,35]
Subjective/objective data	To collect relevant data for all the identified indicators	[7,9–17,22,23,25–27,29–31,35]
Relation between indicators	To address the trade-offs and interdependencies between indicators	[4,6,7,14,23,25,27,30,31]
Assigning weightage for indicators	To assign weights for all indicators to overcome trade-offs	[5,7,13,14,23,27]

2.2.1. Definition of Goal/Scope

Establishing the sustainability assessment's aim and objective is comparable to the first of ISO 14040's four iterative phases of the LCA methodology [36]. Similarly, authors have initiated their research by declaring the goal or boundary for the assessment. Certain authors assessed the product [13,22,29], some the process [10,27,35], some the company/industry [7,31,32], and some the existing technologies [24]. Defining the research aim serves as a roadmap for the remaining phases. The sort of data that will be gathered, the clarity of the data, the type of conclusions, as well as how the results are shown are also considered [10,12]. Several authors have also declared a proper scope by defining "cradle to cradle" and "cradle to grave", among others [27], whereby they set their limits for assessment.

2.2.2. Indicators

To capture the existing scenario as it is and to have accuracy in the result declared, it is important to identify the indicators. The defining goal in the first place helps to identify indicators within a boundary. Sustainability assessment is never an easy task when performed in practice, as each action will have a direct or indirect relation inside an organization, so it is important to set a boundary limit using a proper goal and to identify the indicators that lie within the scope. When selecting metrics for sustainability evaluation, there are numerous important variables to consider. First, the measurements should cover all three sustainability areas adequately. The measurements should also give enough data within each area to provide an accurate picture of performance. Lastly, if the evaluation is to be used to compare alternatives, the metrics must be widely used or adhere to industry standards [37].

2.2.3. Subjective/Objective Data

Industrial operations are complex, and as a result, the data collection methods are even more tedious. From a sustainability assessment perspective, certain authors such as Chen et al. [11] have used subjective data, whereas many of them have used purely objective data for the assessment [4,16,17]. Subjective data refers to surveys, interviews, etc., whereas objective data directly come from a metric that is quantified with real values. The reason behind choosing subjective data over objective data is mainly because of the lack of data existing in the company [12]. In most cases, data were gathered from several sources in the literature, and have been mostly utilized to quantify assessment measures using peer-reviewed conversions.

2.2.4. Relation between Indicators

There exists a major difference between authors in that, right after finding out the indicators, certain authors start to seek out the interdependencies between the indicators [4,11,32], whereas certain other authors [12,35] start to calculate the value of the indicators right away. Identifying the interdependencies helps the organization or the company to find out the trade-offs and pave the way to overcoming them. As assessment systems are complicated, it is not reasonable to assume that the indicators inside them are independent [4]. Therefore, the connections between the indicators must be determined.

2.2.5. Assigning Weightage for Indicators

Identifying relationships between indicators helps the user to sort the indicators based on the priority level [6,14], and prioritization is necessary when several concurrent impacts are present. For instance, developing an eco-friendly product for an environmental dimension affects the economical dimension by increasing the product/process cost. In such a case, prioritization can be made for the indicators, according to the preferences of the decision-makers. To retain these preferences, they must think straightforwardly about what is most important for their company and how much weightage must be provided for each indicator. From a practical point of view, weighting the indicators based on the priority level can reduce complexities for the assessment. The method used by seven of the identified approaches to deal with this need is the AHP [5,7,13,14,23,27]. The most important element of weightage is to not only estimate the importance of the major issues for sustainability, but also to connect these issues and how to collaborate between them to study (sensitivity analysis) the impact effects (significant) on global manufacturing enterprise sustainability [7].

2.3. Data in sustainability Assessment

The sustainability impact assessment is used to analyze the probable effects of a particular project or proposal on the social, environmental, and economic pillars of sustainability [31]. Data-driven sustainability shows the importance of data, which includes collecting and using data to make decisions that guide measurable and sustainable business practices [38]. With recent advances in technology, data are essential to building a sustainable business, and the process of automated data collection and analysis empowers enterprises to make the strategic, real-time decisions needed to achieve sustainability goals [11,39]. However, there are questions to be resolved, such as collecting and storing the Big Data obtained from real-time sensors, which can be appropriately processed to provide the right information for the right question at the right time [10,38].

In addition, cutting-edge technologies can uncover deep insights from data, opening a world of innovative ways to support sustainable practices across organizations [19,38,39]. This handling of large volumes of data means that actions can be coordinated and monitored right along value chains, allowing for the efficient oversight of products and externalities. In this regard, data-driven sustainability demonstrates the importance of data in making decisions that guide measurable and sustainable business practices, helping identify opportunities to improve resource usage, minimize waste, and measure sustainability performance [40,41]. For instance, data-driven sustainability can reduce greenhouse gas emissions and optimize supply chains. Therefore, all insights from data can power positive change while increasing profitability [42].

2.4. Indicators in Sustainability Assessment

Despite the abundance and diversity of methods and tools for assessing sustainability, indicators are one of the most used approaches [43]. Thus, one of the initial tasks in conducting sustainability assessments is to define quantifiable metrics [10]. They provide a measure for the performance and establishment of goals within each dimension: social, economic, and environmental [44]. As with the several and often conflicting factors embedded in the sustainability assessment dimensions, different metrics can be used that may provide useful and different insights to different stakeholders and audiences [10,45]. Sustainability indicators can improve the dialogue with stakeholders, engaging them in sustainability matters and providing key relevant information for their decisions and aspirations [45]. Different decision levels can be considered, namely, process, product, company, or supply chain level. From the revised literature, we see that it is current practice to have three indicators, one for each dimension of sustainability, which could be further aggregated and compiled through weighting procedures into a global sustainability index. The environmental indicator is focused on the impacts made by negative changes to the environment [10]. The most used metrics are related to the efficiency of the production and the use of resources (material, energy, water), waste management and emissions discharge (air, water), and may include impacts on public health. For the social indicator, there is a challenge related to defining the objective given the varying perceptions of social impacts and the mix between qualitative and quantitative measurements [46]. The metrics are related to the health and safety of employees and workers, and stakeholder engagement, which includes supplier diversity, employee diversity, and customer satisfaction, among others [25]. Lastly, the economic indicator addresses how well the company is performing in economic and financial aspects, with the use of net profit and the cost of capital metrics.

2.5. Tools in Sustainability Assessment

Eco-efficiency and resource efficiency are two key aspects in sustainable industries regarding contemporary challenges in mitigating the need for resource extraction, but also to effectively accomplish the decoupling of economic growth from environmental impacts [47,48]. The efficiency framework combines two innovative tools: multi-layer stream mapping (MSM), which assesses overall resource and process efficiency, and ecoPROSYS, used to assess eco-efficiency [49].

In the past decades, remarkable progress has been achieved in terms of productivity gains, with new advanced production technologies and innovative management systems, but also with optimized labor management and the efficient consumption of raw materials. Lean manufacturing principles and related tools have been playing an important role in efficiency improvements, and greatly reinforced organizations' resilience. Lean tools, such as VSM, enable companies to focus on value-added activities and consequently identify waste [50,51]. VSM is a simple and effective method applied for the visualization of value streams, and to make explicit the waste dimension. Based on the VSM principles, but with a broader sustainability mindset, MSM provides an innovative approach to the assessment of the overall efficiency of production systems [52–54]. The great similarity of MSM regarding VSM consists in the identification and quantification, at each stage of the processing system, of "what adds value" and "what does not add value" to a product or service, not only in the sense of "the client", but also "of the Planet" and "the worker". Thus, the MSM concept, besides its original scorecards and algorithm for efficiency aggregation for different aspects of efficiency (resources, operations, flow, etc.), also introduces multiple reasoning for "value definition", not just from "the client perspective". The MSM methodology is composed of four basic pillars that provide it with the capabilities required for the proposed objectives: VSM with the application of lean principles; evaluation variables (key performance indicators—KPI) via efficiency rations; visual management aspects and calculation of the overall efficiency of processes/systems (bottom-up analysis). The MSM results are combined and integrated into the analysis as direct results (efficiency results in percent unit, hence dimensionless), where the NVA (no-value added) helps identify the priorities to reduce waste, the VA (value added) helps identify the part that is currently adding value, abd the Target helps define the VA that is expected to be achieved, hence defining the maximum waste reduction target. Evaluating the MSM methodology and tool, dashboards are obtained together with a color scheme (shown in Figure 2), allowing the quick visualization of the aggregated efficiencies, and enabling access to the desired aggregated efficiency quickly and effectively.

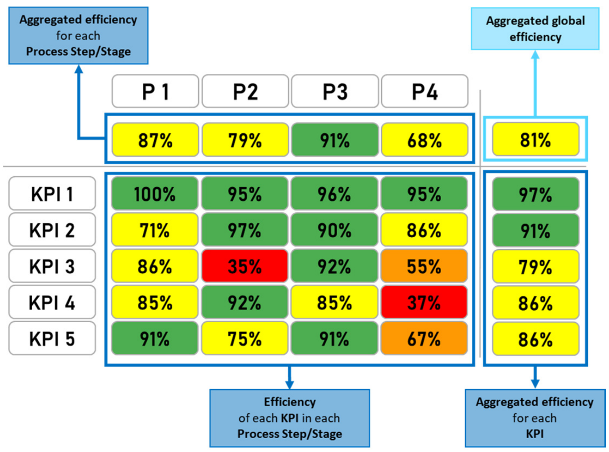

Figure 2. Representation of the MSM scorecard obtained through the MSM tool.

According to the World Business Council for Sustainable Development, to achieve the concept of sustainable development, it is necessary to reconcile economic growth with the balanced exploitation of the environment [20]. Industrial activities and environmental factors should be quantified through the concept of eco-efficiency [55], relating environmental performance with economic performance [56]. To understand and analyze eco-efficiency, the ecoPROSYS methodology is based on the use of an organized set of indicators [49], promoting the best continuous and most efficient use of resources, enabling the maximization of product value creation and the minimization of environmental burdens. The ecoPROSYS is a complex tool that allows the identification of three profiles: environmental, eco-efficiency and cost.

The results of the efficiency framework allow the eco-efficiency and efficiency performance to be assessed simultaneously, using the results of the MSM and ecoPROSYS methodologies. The integrated results of efficiency and eco-efficiency give rise to a new tool (Figure 3)—the Total Efficiency Index (TEI).

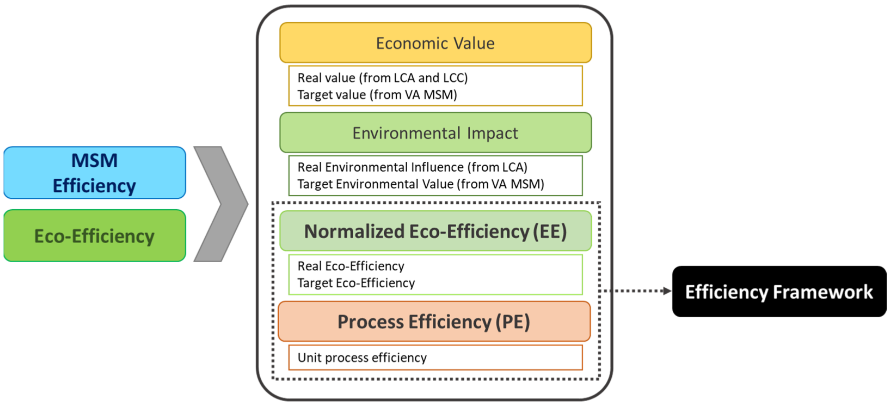

Figure 3. Total Efficiency Index [49].

The TEI is calculated for each process step of the system, and it is obtained, in quantitative terms, by crossing the normalized eco-efficiency value (considers ecology and economy) and the results of the operational efficiency assessment (considers NVA and VA activities), as shown in Equation (1).

$$\text{Total Efficiency Framework [\%]} = \text{Normalized eco-efficiency} \times \text{Process efficiency} \quad (1)$$

The TEI allows the evaluation of the impact of changes in a given system on the environment, the economic component, as well as on production efficiency, enabling the user to make more informed decisions regarding the potential impact of these changes, with the aim of improvement.

According to European Commission, industrial symbiosis is “the process by which wastes, or by-products of an industry or industrial process become the raw materials for another” (European Commission) and has been applied with recognized environmental, economic, and social benefits, such as reductions in operational costs, taxes and emissions of CO_2, and jobs creation [57,58]. To maximize industrial value capturing through the exchange of resources (waste, energy, water, and by-products) between different processes, it is important to engage in industrial symbiosis [59].

A maturity grid was developed by Golev et al. [60] that reflects the barriers and enablers for synergies projects. This maturity grid helps monitor and assesses the level of maturity of potential industrial collaborative initiatives and includes seven IS barriers that are tested against five stages of maturity. To have a clear understanding of the potential industrial symbiosis, it is essential to perform the precise quantification of, and to characterize, the waste and this can be analyzed through the MSM tool. The MSM tool can support the definition of exchange routes between hot (donors) and cold spots (receivers) to underpin industrial symbiosis potential, through the development of solutions bringing benefits for both. Thus, the overall efficiency of the system can increase, and inefficiencies and misuse costs can be reduced [59].

In the industrial symbiosis process’ implementation, it is essential to identify the internal and external factors that can influence the company. Therefore, the SWOT analysis is commonly used to gather information needed to evaluate the positive and negative factors of an organization and complement the final decision-making [61].

3. Framework

Although intense research has been undertaken in the context of sustainability assessment, the literature has so far failed to bring all these crucial elements into one picture to utilize the assessment methodology to the fullest. A guideline that can be used by any sector irrespective of their operational area is not clear from the reviewed literature. Several authors identified data-driven assessment as an essential aspect to implement accurate and continuously improvable sustainability performance in companies (see Section 2.3). Nevertheless, a systemic framework that can interconnect all these elements is still lacking, which could subsequently assist in achieving the objective. Keeping both these aspects was the basis of this research, built on the holistic framework "Data-Driven Sustainability Assessment", here described.

The development process for the framework adopted a structured approach, following the good practices of the literature review, to identify the gaps in the present problems/challenges, as above described. After that stage, the collection of interviews and work sessions coordinated by R&D entities (institutes and academia) was performed within a consortia R&D project (PRODUTECH 4S&C), with end-users from industry (packaging, capital goods sectors) and large supply-chain distributors. Furthermore, technology-provider companies were also interviewed to assess typical issues and challenges in technical digitalization requirements, data collection, data storage, data processing (data analytics and predictive analytics). With this information, brainstorming sessions were carried out, firstly to design the main architecture of the framework concept that was then presented to the industrial partners. Feedback was taken to allow iteration for improvements, and finally a pre-validation was performed. Finally, the full design and detailed framework were developed and presented to the industrial companies for final feedback and iterative improvement.

The resulting sequential framework built in this paper can be used irrespective of the application area and can support organizations in implementing and assess sustainability based on data (Figure 4). The proposed framework aids companies in determining the best techniques and tactics to use in a specific circumstance based on what is required to reach towards a more sustainable performance. It also helps the organization to clearly understand the objective and prepare themselves to achieve it. By following this approach, a development graph can also be visualized over a period to establish a motivating culture that can support continuous improvement. As a result of using a data-driven sustainability approach, new opportunities such as industrial symbiosis and circular economy can also open up. The steps are depicted in the next paragraphs.

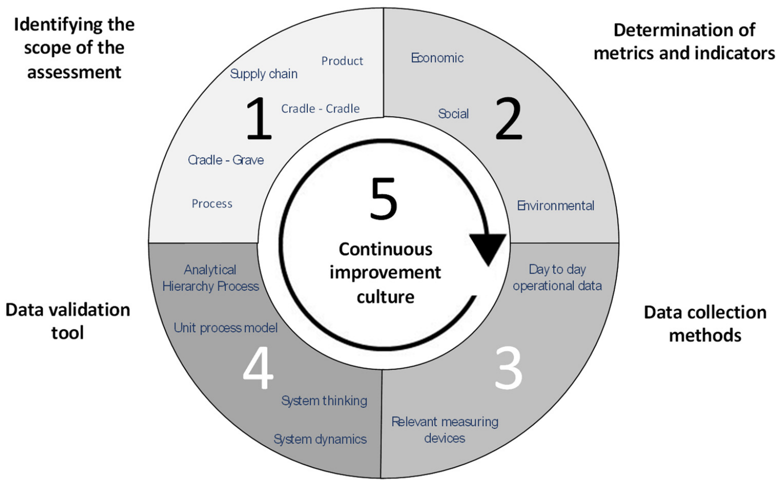

Figure 4. Framework for data-driven sustainability assessment.

Step 1. Identifying the scope of the assessment

Life cycle thinking is defined as a way of thinking about the environmental, social, and economic impacts of a product or a system over its entire life cycle. The environmental impacts are quantified through LCA, a standardized methodology [36] that measures the potential environmental impacts of a product or a system throughout its life cycle stages. The results of an LCA study are directly related to the defined goal and scope—the goal comprises clear and unambiguous information about the intended application, the reasons for carrying out the study, the intended stakeholders and how the results are intended to be used, and the scope defines the details and dimensions of the study in relation to reaching the goal [36]. Regarding decision-making by stakeholders, there is a need to consider the entire life cycle, which goes from obtaining everything needed to make the product or system, through manufacturing, use, and finally, deciding what to do when it is no longer useful. Thus, there are some different definitions of scopes, such as "cradle to grave" (the product or system goes through its entire life cycle, from the time it is produced until it reaches its end of life), "cradle to gate" (the manufacturing phase only) and "cradle to cradle" (an alternative processes to end of life, such as recycling, retrofitting and refurbishing, among others) [62]. In this type of assessment, it is important to define the functional unit and the system boundaries to determine the intended focus [62]. The system boundaries will help to identify the main mass and energy flows that occur within the system. These flows need to be quantified and analyzed, considering as reference the previously established functional unit that quantifiably measures the outcomes or main function of the product system. The economic assessment can be quantified through LCC methodology to determine the most cost-effective options presented at different life cycle stages, and analyzes different costs for the intervening stakeholders, while also considering externality costs that are not usually accounted for, but are of great relevance in a sustainable and circular economy. In this approach, the goal may be a comparative analysis, and the scope includes the system units, the definition of the subject of the study, and the assumptions and limitations [62]. Throughout the life cycles of a product, S-LCA is a part of the LCSA, and it is presented as the most effective technique to assess the social and socio-economic impacts of a product [63]. In this assessment, workers/employees, the local community, society, consumers, and value chain actors are the five categories of stakeholders to be considered. This methodology is based on the LCA methodology and was developed in accordance with ISO14040 and ISO14044 [63]. Normally, the definition of the goal and scope is the first phase of these methodologies, and these first steps are relevant to the assessment, because this is where the exact approach is determined, and the choice of life cycle inventory depends on the goal and scope definition.

Step 2. Determination of metrics and indicators

For sustainability assessment, it is crucial to define metrics that allow measuring. Several approaches have been used to define these metrics. Hossaini et al. [23] developed a sustainability assessment approach to identify a broad range of environmental and socioeconomic impacts of construction and buildings. This approach was based on the so-called TBL sustainability criteria, which combine LCSA with a systemic method for decision-making (AHP), and uses 18 indicators of TBL sustainability. Regarding the environmental level, it considers 12 indicators, mostly quantitative and associated with the LCA (for instance, fossil fuel depletion, global warming potential, eco-toxicity, and waste management, among others). At the social level, social impact was assessed through formal interviews with construction managers, wherein the various qualitative criteria chosen for this purpose were compared (for instance, occupant comfort, safety, seismic resistance, fire resistance and affordability). Lastly, on the economic level, the authors considered the overall cost of the building per phase through an LCC with the Net Present Value (NPV) method.

From a different perspective, Ghadimi et al. [13] developed a weighted fuzzy assessment method (WFAM) for product sustainability assessment. The authors selected a group of elements based on the triple bottom of sustainability (economic, environmental, and social) as well as a group of sub-elements (seven), and implemented a weighted fuzzy logic method. The sub-elements were based on a literature review of relevant indicators for sustainability assessment, and were also confirmed through expert consultation. In this case, the sub-elements were environmental (greenhouse and pollution); economic (cost, resource, technology, and process) and social (social performance). Through a fuzzy scale, four experts performed a paired comparison of the relative importance of the elements and sub-elements, first comparing the main elements with the total sustainability index, and then the sub-elements with the main elements. Afterwards, the elements and sub-elements were weighted based on the FAHP methodology. Finally, data collection was developed to characterize the influencing factors.

Shuaib et al. [15] proposed the Product Sustainability Index (ProdSI), a metric-based methodology that provides a comprehensive assessment of the overall product sustainability throughout its total life cycle (pre-manufacturing; manufacturing; use; posture). The authors used a top-down perspective, starting with the general index level (ProdSI), which identifies which elements of the product should be measured and analyzed. The indicators are thus structured according to a hierarchy of five levels: the aggregated index (ProdSI) (i); the sub-indices, which characterize the TBL (environment, society, economy) (ii); clusters, corresponding to more general elements of the TBL sustainability factors (iii); sub-clusters, which break down clusters into more specific elements of sustainability (iv); individual metrics, which are quantifiable and measurable attributes related to a single sustainability parameter or indicator (v). All of these are measured throughout the product's lifecycle. In terms of the indicators used for the assessment, the authors considered 13 indicators in total. Regarding economics, the initial investment, direct/indirect costs and overheads, benefits, and losses were considered. At the environmental level, the material uses and efficiency, energy use and efficiency, other resources use and efficiency, waste and emissions, and product end of life were addressed. Lastly, at the social level, the indicators were product quality and durability, functional performance, product end-of-life management, product safety and health impact, product societal impact regulations, and certification. Shuaib et al. [15], in their assessment, recognized the importance of considering all factors related to the product, such as its production, use, and end of life, and they therefore gained a broader perspective of quantification for the overall product's sustainability (total life cycle evaluation) beyond just the existing product.

Another approach used to identify indicators is through modeling and simulation, as found in [10,29]. Through an input/output-based foundation, mathematical models are elaborated for each of the product life-cycle stages. The indicators are generated by accounting for the manufacturing process, wastes and effluent emissions, labor, energy, raw materials, packaging, water use, and product data. The integrated approach allows for using life-cycle inventory data to build a sustainability assessment model. In both previous approaches, the input/output modeling serves as the basis for the mathematical foundation of the indicators.

Despite this, each study refers to different metrics appropriate for the case study at hand, and no universal formula is available. There is a pool of sustainability metrics available in each of the three pillars, and it is the role of the company to choose the appropriate ones. Therefore, metric selection is a company-specific process, and needs to reflect the values of the company, the established objectives in terms of the sustainability pillars, as well the available data. Indicators should be highly aligned with the company's capabilities and commitment to sustainability. An important point to highlight is that the authors recognize the importance of involving experts, operational managers, and higher management in the selection of the sustainability indicators, using the experts' opinions to validate the selected sub-elements and influencing factors [13].

A common point around previous methodologies is that there is a need to obtain data to construct indicators. Sustainability indicators deal with multidisciplinary data and often from conflicting business activities, and the nature of sustainability implies a need to deal with reality, where the "value of official data is in question" [64]. Therefore, there is an additional effort to acquire, compile and have at one's disposal a vast amount, and different types, of data. Moreover, a discussion on sustainability indicators by Ramos [64] revealed that even if data are compiled, stakeholders feel that either the information is not easily accessible or usable, or it is incomplete, or sometimes obsolete, by the time it reaches the user [65].

Therefore, improving the handling and flow of data is mandatory. The next steps deal with data management in the context of a data-driven sustainability assessment.

Step 3. Data collection methods

Defining the metrics and indicators paves the way to building a data collection method. Traditionally, data have been utilized to better manufacturing's technological and economic elements. In this regard, a well-informed and well-planned data collection and analysis plan may help manufacturers achieve greater sustainability [19]. The development of a data collection and analysis plan must be considered in order for it to make a greater contribution to sustainability in manufacturing [40]. In this sense, with the emergence of data identified as big data, there is now a major trade-off between the size, time, quality, and cost of information generation that cannot be dealt with in terms of traditional business intelligence capabilities [38]. As with any data, sustainability data can be best described with the six V's of Big Data [66]: Volume, which is the main feature of big data and is mainly about the relationship between size and processing capacity. This aspect changes rapidly as data collection continues to increase. Variety, which describes the wide variety of data that are being stored and still need to be processed and analyzed. For example, the different kinds of sustainability data collected, whether environmental, social, or economic. Velocity, which describes the frequency of data collection. Value, which describes what value you can get from which data, and how Big Data gets better results from stored data. Veracity shows the quality and origin of data. Variability describes data inconsistency as a common scenario that arises as the data are sourced from different sources.

Regarding the definition of measurements and indicators, some works present the following strategies and paths to develop data collection methods. Armstrong et al. [12] used a data collection approach based on subjective data, collected from several literature sources, including data regarding the density of landfill waste, automobile emissions, electricity generation, the conversion of methane and nitrous oxide emissions to carbon dioxide emissions, and risk assessment. The choice of available literature sources was related to the lack of available data inside the company.

A holistic sustainability assessment tool has been used for manufacturing SMEs, using a questionnaire to collect the data [11]. This questionnaire included 133 questions divided into several functional areas, classes, and themes. The questions were mostly quantitative and provided the main indicator, namely, the Sustainability Theme Index.

The methodology created by Eastwood and Haapala [10] used an objective data collection method, since these data were generated from the aggregation of sustainability performance metrics, considering several key aspects, such as economic, environmental, and social. A similar approach to developing a sustainable manufacturing assessment framework for Indonesian SMEs was created by Fathima et al. [22]. All data were based on well-defined sustainable manufacturing criteria, such as technical (e.g., reliability), economic (e.g., costs, sales), environmental (e.g., solid waste, greenhouse gas emissions), and social (e.g., employment opportunity, warranty). Faulkner et al. [26] developed a methodology for sustainable value stream mapping using data generated mainly from environmental and societal metrics. Within the environmental metrics, the proposed framework collected data related to the amount of water needed, used and lost for each step of the process; data about raw material usage, and energy consumption data. The societal metrics generated data regarding physical work, such as the Physical Load Index, and work environment data, such as potential operator risks.

In the work proposed by Foolmaun and Ramjeawon [16], the data were acquired by a survey questionnaire from the primary stakeholders engaged in the four outlined scenarios. The questionnaire included indicators for the three stakeholder categories, as well as eight subcategories, and it was written straightforwardly with simple yes or no questions. Three powerful tools—LCA, LCC, and S-LCA—were used for evaluation. In the study by Garbie [7], the data were gathered based on two factors: the current value of the indicator performance measure (current), and the indicator's desired value (benchmark). These types data are determined by how the questions are answered, and some inquiries are quantitative in nature, while others are qualitative in nature. Finally, full analytical and quantitative models are given, and discussions are undertaken of the value of performance metrics, starting with the individual indicator, issue/aspect, and progressing to the general sustainable development index, to achieve optimal measurement of their impact on others by balancing between dimensions of sustainability [7].

In general, understanding the importance of data analysis is not the main obstacle to sustainability assessment. Data have traditionally been used to improve the technological and economical aspects of manufacturing [40]. The challenge posed by Big Data and data collection is to determine the relevance of the available data to sustainability assessments, such that this information can serve as a guide for planning with greater security. This suggests the need to replicate and extend the research for a greater understanding of each activity area, and to develop appropriate indicators [19,39].

Step 4. Data validation

In today's world, most organizations work in a complex environment irrespective of the application area. So, to have a clear understanding of the collected data, an organization needs to determine the relationship between the indicators. The indicators related to the data will represent the results for environmental, economic and social dimensions independently, but a company must understand the interdependencies and trade-offs between them. Multiple authors have already used mathematical models to understand the data and to perform sustainability assessments. Hossaini et al. [23] developed a sustainability assessment approach based on the LCSA method combined with a systemic method for decision-making AHP, applied to a case study from the construction industry. Ghadimi et al. [13] applied, within the scope of a case study of an automotive component manufacturing organization, an indicator-based sustainability assessment approach, interpreted through weighted fuzzy logic. Similarly, a mathematical tool must be included in the framework, where the collected data can be usefully interpreted to understand the trade-offs between factors. This also serves to improve the effectiveness of the assessment.

Therefore, while in Step 2 the main objective is to select/define the necessary metrics/indicators to assess the triple dimensional perspectives, in Step 4, a deeper analysis is proposed to identify a relationship between metrics, thus giving useful meaning to the collected data regarding sustainability assessments. In this way, several related indicators are brought into the pool of analysis in Step 2, and in Step 4, the interdependences and overlaps are identified so as to develop a comprehensive but concise set of indicators. A validation tool allows for the selection of a set of indicators that supports a holistic sustainability assessment decision-making process, covering the three perspectives while avoiding duplicated analysis. As visualized in Figure 5, selected indicators based on the triple dimensions will have multiple interdependencies between them; for example, when the environmental impact is reduced by using a more appropriate raw material (i.e., metal over plastic), the economic factor will be affected. Making these dependencies evident within the organization will support decision-makers in making suitable decisions.

Step 5. Continuous Improvement

The main aim of this step is to explain how data-driven sustainability assessments can enable a continuous improvement culture inside an organization. The realization that sustainability is not a binary term with only two states, sustaining and not sustaining, but rather has a variety of states is crucial to the creation of a sustainability model [21]. To understand this better, Figure 6 depicts two levels (Type A and Type B) of sustainability that vary when treated differently.

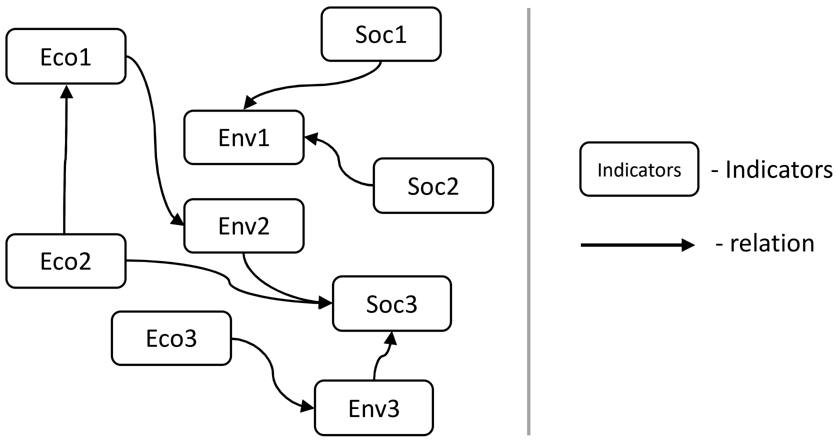

Figure 5. Data validation results.

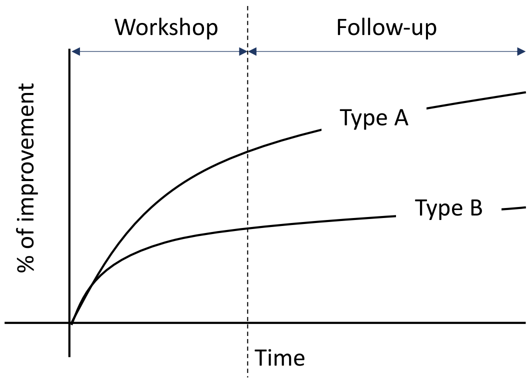

Figure 6. Continuous improvement chart.

In the previous steps, scope, indicators and data relations are determined, and the current state of sustainability is measured. Nevertheless, to develop a continuous improvement culture (Type A), it is obligatory to review the state of the organization consistently. Data-driven sustainability assessment would be the right solution to achieve Type A. As the framework is built by emphasizing data, the result not only represents the areas for improvement, but also helps the user to continuously review the state and to set new target values.

4. Discussion and Conclusions

Sustainability is a crucial topic in the modern day, compared to the past. Government regulation, compliance issues, as well as market requirements push organizations to develop sustainable products and deliver cultural transformations. It is important for an organization to understand where they currently stand in terms of sustainability, and what capabilities and aspects are needed to implement more sustainable outcomes. In this sense, there is a need for holistic tools to evaluate the current state of an organization in relation to the implementation of sustainability actions. The literature review shows that a data-driven sustainability assessment would be a good means of addressing this challenge. Additionally, reliable sources, organized data collection, and well-suited analysis approaches should be used, in order to derive the maximum benefit and assure reliability in automatic data acquisition and processing. Together with these two aspects, it was found that accountable and understandable KPIs are a necessity together, with monitoring, to support continuous improvement practices.

These requirements are met by the five-step framework proposed in this paper, supporting organizations through a systematic process to facilitate the integration of data-driven sustainability principles in companies. To start, Step 1 urges companies to define the scope of the assessment, which could be a process, product, or organization, up to the supply chain level. Moreover, holistic considerations regarding the life cycle should be addressed here. In Step 2, the most relevant metrics and indicators should be defined, in accordance with the proposed scope of the assessment. The identified metrics and indicators should also reflect the company's objectives with the assessment. In the selection of the sustainability indicators, experts, operational managers, and higher management should be involved. In Step 3, the data-driven approach necessitates the establishing of data collection procedures, as planning greatly increases its potential to enhance sustainability in companies. An implication of the advancements in Big Data and Industry 4.0 is that they increase the need to assess the relevance of the available data. Step 4 focus on the data validation stage, which allows the identification of the trade-offs between assessment indicators when using data. Namely, the interdependencies between all three indicators of sustainability (economic, environmental and social) are identified to better support the decision-making. Finally, in Step 5, the aim is for the practitioner company to adopt a continuous improvement culture in terms of sustainability assessment and action implementation, cross-linking lean thinking with direct sustainability indicators in a process of TBL. This can foster a surge of opportunities such as industrial symbiosis models and more circular economy actions, making this strategy align with the three pillars of Industry 5.0, namely, human-centricity, sustainable development and resilience to crisis [67].

The framework adopts a holistic approach that applies irrespective of industrial sector, and it can be handled by any organization, irrespective of their area of operations. In fact, this is one of the innovations of the proposed framework, as the published approaches and methods are all case-specific, specific company-driven, or specific product-driven (Table 1). In addition to the universality of the proposed approach, another innovation is the integration of several requirements to assure the reliability, understandability, and improvability of the sustainability assessment. In fact, some of the published approaches fall short in several aspects: (i) objective definition of the goal/scope, (ii) assuring relevant data collection methods, in accordance with data-driven approaches; (iii) lacking quantitative data (KPI) as well as indicators' weights and interrelations (Table 2); (iv) lacking an embedded continuous improvement mentality, which was not found in any of the 28 studies analyzed, thus representing another innovation of the proposed approach.

This discussion confirms that, although different literature sources emphasize using data-driven sustainability assessments, a step-by-step guide that enabled a continuous approach to assisting sustainability implementation was lacking.

As the main recommendation for future studies, the authors advise the validation of the proposed holistic framework in practical cases, in different sectors, which will allow for strengthening the framework and its implementation results, while considering the balance between the generality and applicability of the framework. This will also reinforce the data-driven models, and develop the discovery and customization of data analytics for specific companies' and sectorial needs.

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Abbreviations

AHP	Analytic Hierarchy Process
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCSA	Life Cycle Sustainability Assessment
LCC	Life Cycle Cost
MCDM	Multi-Criteria Decision-Making
MSM	Multi-Layer Stream Mapping
NVA	Non Added Value
NPV	Net-Present Value
ProdSI	Product Sustainability Index
VA	Added Value
S-LCA	Social Life Cycle Assessment
TEI	Total Efficiency Index
TBL	Triple Bottom Line
VSM	Value Stream Mapping
WFAM	Weighted Fuzzy Assessment Method

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