sustainability

MDPI

Article

Technological Sustainability or Sustainable Technology? A Multidimensional Vision of Sustainability in Manufacturing

Marco Vacchi [1], Cristina Siligardi [1], Fabio Demaria [2], Erika Iveth Cedillo-González [1], Rocío González-Sánchez [3] and Davide Settembre-Blundo [3,4,*]

[1] Department of Engineering "Enzo Ferrari", University of Modena and Reggio Emilia, 41125 Modena, Italy; marco.vacchi@unimore.it (M.V.); cristina.siligardi@unimore.it (C.S.); ecedillo@unimore.it (E.I.C.-G.)
[2] Department of Economics "Marco Biagi", University of Modena and Reggio Emilia, 41121 Modena, Italy; fabio.demaria@unimore.it
[3] Department of Business Administration (ADO), Applied Economics II and Fundaments of Economic Analysis, Rey-Juan-Carlos University, 28032 Madrid, Spain; rocio.gonzalez@urjc.es
[4] Gruppo Ceramiche Gresmalt, Via Mosca 4, 41049 Sassuolo, Italy
* Correspondence: davide.settembre@gresmalt.it

Abstract: The topic of sustainability is becoming one of the strongest drivers of change in the marketplace by transforming into an element of competitiveness and an integral part of business strategy. Particularly in the manufacturing sector, a key role is played by technological innovations that allow companies to minimize the impact of their business on the environment and contribute to enhancing the value of the societies in which they operate. Technological process can be a lever to generate sustainable behaviors, confirming how innovation and sustainability constitute an increasingly close pair. However, it emerges that the nature of this relationship is explored by researchers and considered by practitioners almost exclusively in terms of the degree of sustainability of technological solutions. Lacking is an in-depth exploration of how a product or process, in addition to being environmentally and socio-economically sustainable, must or can also be technologically sustainable. This research therefore aims to build a theoretical foundation for technological sustainability seen as a possible fourth dimension of sustainable development.

Keywords: technological sustainability; manufacturing; sustainability; technology; impact assessment

check for updates

Citation: Vacchi, M.; Siligardi, C.; Demaria, F.; Cedillo-González, E.I.; González-Sánchez, R.; Settembre-Blundo, D. Technological Sustainability or Sustainable Technology? A Multidimensional Vision of Sustainability in Manufacturing. *Sustainability* **2021**, *13*, 9942. https://doi.org/10.3390/su13179942

Academic Editor: Antonella Petrillo

Received: 15 August 2021
Accepted: 2 September 2021
Published: 4 September 2021

1. Introduction

Technology and sustainability should be considered key factors in a company's competitiveness, since without these factors it is more difficult to achieve positive results and keep them over time [1]. Together, technology and sustainability enable companies to achieve higher earnings, reach new markets, expand their customer base, and increase their margins. However, for this to happen, firms need to embed technology and sustainability within their strategies and corporate culture [2], as well as invest in them and take action to address results and continuously monitor performance [3]. Nevertheless, especially in a managerial environment, when talking about sustainability, there is a tendency to consider the environmental, economic, and social dimensions as separate and independent elements [4,5]. What is still missing is an understanding of the strong interconnections that bind the different dimensions of sustainability that are linked together and enabled by technology, which is a fundamental driver of business development [6].

1.1. Background

With the growing use of digital platforms, technological innovation is currently helping manufacturing companies to adopt sustainable processes and practices by making available a series of innovative solutions that can support the path to responsible production [7]. However, for a company to take full advantage of this opportunity, sustainable practices must extend to all stakeholders in the production chain and to all phases of a product's life cycle [8]. Indeed, sustainability requires the adoption of a systemic approach and a holistic vision with the application of 4.0 technologies to the entire production process to enable the reengineering of products, business models, and logistics supply chains in a sustainable way [9].

On the other hand, the current concept of sustainability is the result of a growing awareness of its multidimensionality [10,11]. In a seminal work, Osorio [12] defined sustainability as the ability of man to maintain a certain system in a state of equilibrium. At the same time, the concept of development has also changed over time to include multidimensionality as a characterizing factor as well as the multiplicity of objectives [13]. Multidimensionality is expressed by the definition of sustainable development that includes the three pillars or the three dimensions of sustainability [14]: environmental sustainability (ability to protect the environment and preserve the resources offered by the planet); economic sustainability (continuous ability to generate profit, welfare, and wealth while respecting what surrounds us), and social sustainability (ability to ensure social welfare to every individual in the world in an equitable manner). According to Braccini and Margherita [15], each of these dimensions is a necessary but not sufficient condition for achieving sustainability because they interact, overlap, and sometimes conflict with each other.

The concepts of sustainability and technology are associated together mainly with the meaning of sustainability of technologies, explored primarily in the environmental dimension and more rarely in the economic and social ones [16]. In fact, the environmental approach to sustainability is prevalent and refers to an equilibrium situation that can be maintained over a long period without depleting natural resources or causing serious damage to the environment [17]. When this definition is translated to the domain of technology, it usually means the possibility that companies have to progress through development and innovation, but without forgetting to consider the respect of natural resources [18]. This approach to production is referred to as sustainable manufacturing [19] or even green manufacturing [20] and is an operational model that integrates product and process design with production planning [21]. The aim is then to identify, quantify, assess, and manage material flows, energy, and water consumption, air emissions, and waste generation, maximizing resource use efficiency and minimizing environmental impact [22]. In this framework, the sustainable manufacturing domain thus covers three areas: production technologies (facilities and equipment), products and their life cycles, and the organizational contexts in which value is created (manufacturing firms and supply chains) [23].

In economics, the term manufacturing is used to indicate the sector that, through production processes, transforms raw materials into manufactured goods, i.e., products that satisfy utility and consumption needs [24]. As part of the development of a product that is able to meet the needs of consumption, a crucial role is assumed by the engineering activities. Based on the outputs of the design processes, the engineering activities verify the technical feasibility of the product in terms of raw materials, constituent components as well as processes, ensuring qualitative compliance with reference standards [25]. It follows that there is both product engineering and process engineering integrated and interdependent with each other [26]. The engineering establishes the characteristics of a product by determining the relationship between quality and costs that, by the way, depends on the performance of the process, also expressed by the relationship between quality and costs [27]. Business decision-makers must therefore resolve the technological trade-off (incompatibility) between costs and quality both of the process and of the products looking for the best solution that maximizes the quality and minimizes the costs [28]. The technological trade-off is not the only challenge facing manufacturing companies. Attention to sustainability (especially environmental sustainability) has now become an ever-growing business necessity [29], not only for compliance or reputational reasons, but also because of the widespread presence of ESG (Environmental, Social, and Governance) funds [30].

These funds by statute are expected to invest in sustainable companies, as well as those that pay attention to the well-being of employees and collaborators and to the respect of governance rules. For companies, therefore, two additional sustainability trade-offs arise.

- Environmental trade-off [31]: is environmental sustainability economically viable, or is it increasingly difficult to find the resources needed to finance the ecological transition?
- Social trade-off [32]: how consistent is social equity with the goal of economic efficiency?

Even the orientation of European policies, for example with the programming of structural funds 2021–2027 (Next Generation EU), propose a paradigm of development achieved through the integration of economic growth with social inclusion and environmental sustainability [33]. In other words, business and profit goals must go hand in hand with social and environmental responsibility issues, no longer considered as alternatives to be balanced in a difficult equilibrium, but as mutually reinforcing pillars [34]. Reconciliation of conflicts related to environmental and social trade-offs, however, should also consider reconciliation of technological trade-offs [35,36], but not only. From a perspective of effective sustainable manufacturing, conflict reconciliation should take a holistic view and include all three trade-offs (environmental, social, and technological) simultaneously [37].

With this approach, economic sustainability, understood as the economic viability of a process or product, becomes the common thread between environmental and social sustainability [38]. Therefore, within the framework of sustainable development, in order to ensure the growth of manufacturing companies and social systems in which they operate, it is appropriate to raise the issue not only of sustainability of technologies [39], but of an effective technological sustainability. In fact, the question of the technological feasibility of a product or a process cannot be separated from its environmental and socio-economic impact [40]. In other words, a process or a product, as well as minimizing the impact on the environment and society and being economically viable, must also be a technically feasible solution and have technological performance that complies with applicable standards.

1.2. Gap Identification and Research Aims

The scientific literature shows that the concept of "*technological sustainability*" is often used as a synonym for "*sustainability of technologies*" emphasizing mainly their environmental dimension and, to a lesser extent, their social and economic one. Confirming this, it is clear that in the few studies published on "*technological sustainability*", scholars refer to sustainable technologies [41], components of economic sustainability [42], environmental sustainability [43], sustainability of technological processes [44], sustainability of (mobile learning) m-learning [45], exergy [46], personal access devices (PDAs) [47], capabilities to reduce ecological impact [48,49], components of sustainable development [50], technological competitiveness [51], degree of how technology affects other dimensions of sustainability [52], and intellectual infrastructure of technological development [53].

Based on the above statements and at the current state of our best knowledge, we can conclude that there is a gap in the scientific literature regarding the concept of technological sustainability. Scientists do not attribute to this term an unambiguous meaning, but above all there is a lack of vision of technology as an integral part of sustainability on the same level as the other dimensions: environment, economy, and society. Given these premises, we address the following research questions.

- *RQ1*: Can a conceptual framework arise from a manufacturing context to ascribe technology as a key dimension of sustainability?
- *RQ2*: Is it also feasible to design a model for assessing technological sustainability?

Therefore, this exploratory paper aims to define a conceptual framework for technological sustainability and develop a method for its assessment in manufacturing, both from an organizational and product perspective.

2. Research Design and Methodology

The RQs previously stated call for a methodological approach capable of resolving the uncertainty and complexity of the topic of technological sustainability, which is still under-researched. The constructivist paradigm has been considered more appropriate for the creation of an explanatory model of the real world as it is that of the manufacturing environment. In such a model, the knowledge building is due to the two-way interaction between the researcher's experience and ideas with the sociocultural context in which he/she acts; thus subject and context are interactively linked [54]. Following this constructivist approach, the theoretical framework was built using inductive inference. For this purpose, empirical data from both secondary (literature, best practices, international standards and guidelines) and primary (direct observation of a factory reality) sources were processed simultaneously. The factory reality that was observed as a primary source of data is an important Italian company that produces ceramic tiles for the building industry, already studied by the authors to carry out research on sustainability management [8,34]. Finally, through abductive inference [55], empirical and real-world observations were transformed into an explanatory model for technological sustainability, which is aimed at answering the RQs posed above. The abductive logic has already been applied in the managerial field in those cases where it takes its cue from the existing theory and then develops a new theory to better understand and interpret organizational phenomena [56,57].

3. Theoretical Framework

A general definition of sustainability can be obtained by inductive inference, synthesizing the scientific contribution of other scholars. In this sense, it is possible to consider sustainability as an intrinsic property of a system [58,59], that is the ability of a complex organization structured in processes to perpetuate itself over time while maintaining its structure and functions unchanged by integrating its economic, social, and environmental dimensions [60,61]. In manufacturing, sustainability [62] is a set of operational best practices [63], enabled by digitization [64], aimed at reaching and maintaining the point of equilibrium [65] where all production factors [66] are consumed at least as intensively as they can be regenerated [67]. Therefore, based on what has been said above, we argue that:

Proposition 1 (P1). *The concept of sustainability is related with change to indicate the capability of a natural, economic, and social system to maintain its intrinsic properties, a continuous process where these three fundamental dimensions interact and are interdependent.*

Proposition 2 (P2). *Sustainable manufacturing is a system that integrates product design, process design, and operating practices while maximizing resource use efficiency.*

Sustainability requires an assessment of the environmental [68], social [69] and economic [70] impacts of products, processes, and organizations [71,72]. Currently, the most widely used framework for these assessments is Life Cycle Thinking (LCT) [73], which considers all the phases and processes that contribute to the manufacturing of a product, including the use and end-of-life phases [74], according to the cradle-to-grave approach [75]. The perspective of analysis can be the product [76], the process [77], or the organization [72] that controls manufacturing. The LCT is a tool to support decision-making and to develop regulatory frameworks or industrial strategies [78]. It is enabled by scientific methods such as Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (S-LCA) used respectively to determine the environmental, economic, and social impacts of a product, process, or organization [73]. LCA is a methodology standardized by ISO 14040:2021 that defines the principles and framework in which the analysis should be performed [79]. In contrast, LCC does not yet have a recognized standard for products and services; instead, there is the ISO 15686-5 standard for buildings and constructed assets [80]. S-LCA also does not refer to an ISO standard, but to the UNEP guidelines updated in 2020 [81]. The three methods share the same analytical framework defined by ISO 14040 for LCA, namely four steps: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment, and (4) interpretation [82]. Environmental impact assessment can also be combined with economic [83] or social [84] impact assessment to get a more complete view of the degree of sustainability. Alternatively, LCA, LCC, and S-LCA can be integrated with each other in a holistic methodological approach called Life Cycle Sustainability Assessment (LCSA) [85]. Consequently, we postulate that:

Proposition 3 (P3). *Life Cycle Thinking (LCT) allows the social, economic, and environmental dimensions of the sustainability of a product, process, or organization to be brought into a single relationship by assessing its impacts from a life cycle or supply chain perspective.*

In accordance with ISO 14040, one of the most critical steps is the Life Cycle Impact Assessment (LCIA), which establishes the relationships between each life cycle stage and the corresponding sustainability impacts [86]. Especially in the environmental field, there are many database-driven methods available to determine impacts [87]. As they are very different, the choice of database can influence the final results of sustainability studies [88]. In the social domain, on the other hand, the assumption is that any human activity, therefore including manufacturing, has the power to create or destroy value [89]. This occurs through the transformation (process) of inputs (resources) into outputs (products) and outcomes (results) which have a direct or indirect influence on the context of reference [90,91]. The changes induced or caused by the input transformation process are the impacts generated in the general environment in which the organization operates, both in the short and long term [92]. The impacts are therefore that part of the outcomes that are attributed exclusively to the activities carried out by the organization. The causal chain that links inputs to processes, processes to outputs, outputs to outcomes, and outcomes to impacts is known as the Theory of Change (ToC) [93]. We formalize this as follows:

Proposition 4 (P4). *In a general perspective of sustainability, impact can be seen as a change or modification of the context in which an organization operates due to anthropogenic activities.*

In accordance with [94], in the social sciences the abductive approach becomes central because it allows shifting the focus from the result to the process and from theory to the formulation of innovative hypotheses. Abductive inference begins with an observation or a set of observations that, according to rules we already know, help us to formulate a hypothesis that can explain the result we have observed. The conclusion of this reasoning is a hypothesis, i.e., a possibility that must be verified [95]. In the specific case of this research, the abductive inference from the theoretical framework is the following:

- Rule: the sustainability of a natural, economic, or social system is the capability to maintain its state, unchanged by anthropogenic activities.
- Observation: in order to be efficient, a manufacturing system must maintain a balance between the technological performance of process and product.
- New explanatory hypothesis: (perhaps) the maintenance of the operational performance of a manufacturing system represents its technological sustainability.

Based on this new explanatory hypothesis, the theoretical framework shows the relationships between the different topics by suggesting the following assumptions:

1. The degree of technological sustainability of a manufacturing company is dependent on its capability to optimize the production factors, ensuring that the organization will continue to operate in the future, at least in the same way as it does today.
2. A technological sustainability assessment should also follow the same life cycle approach as provided by the LCT and the same analysis steps set by ISO 14040. This methodological consistency with the main methods of sustainability assessment can indeed facilitate their integration following a holistic perspective for environment, economy, society, and technology.

4. Technological Sustainability Assessment (TSA)

Following the life cycle approach (LCT) and supply chain perspective, a methodological framework for technology sustainability assessment is proposed in this section, based on the best practices developed in the European Commission-funded project LIFE Force of The Future [96]. The aim is to provide a tool for managing the impact of technology in manufacturing industry that can assist companies' decision-making processes, following the ISO 14040 logic framework.

4.1. Definition of the Goal and Scope of the TSA

The first step of the TSA was to define the objectives of the study, specifying the motivations behind the work and the information expected to be obtained as a result. Similarly to other sustainability assessment tools, two different approaches can be adopted to capture the technological dimension of sustainability: (1) the perspective of the product and its manufacturing process with which the product is closely associated [97]; (2) the organization that operates the manufacture and sale of the product from a business viewpoint [98].

The unit of analysis in the first approach is the functional unit that defines the product system to be analyzed, while in the second approach is the organization under study. Adapting the activities categories defined by Porter [99] to describe the value chain of a business, as already done in other recent studies [100], the pattern of possible system boundaries (cradle-to-gate and gate-to-grave) was drawn (Figure 1) for the assessment of the technological sustainability of the product process (P-TSA) or organization (O-TSA).

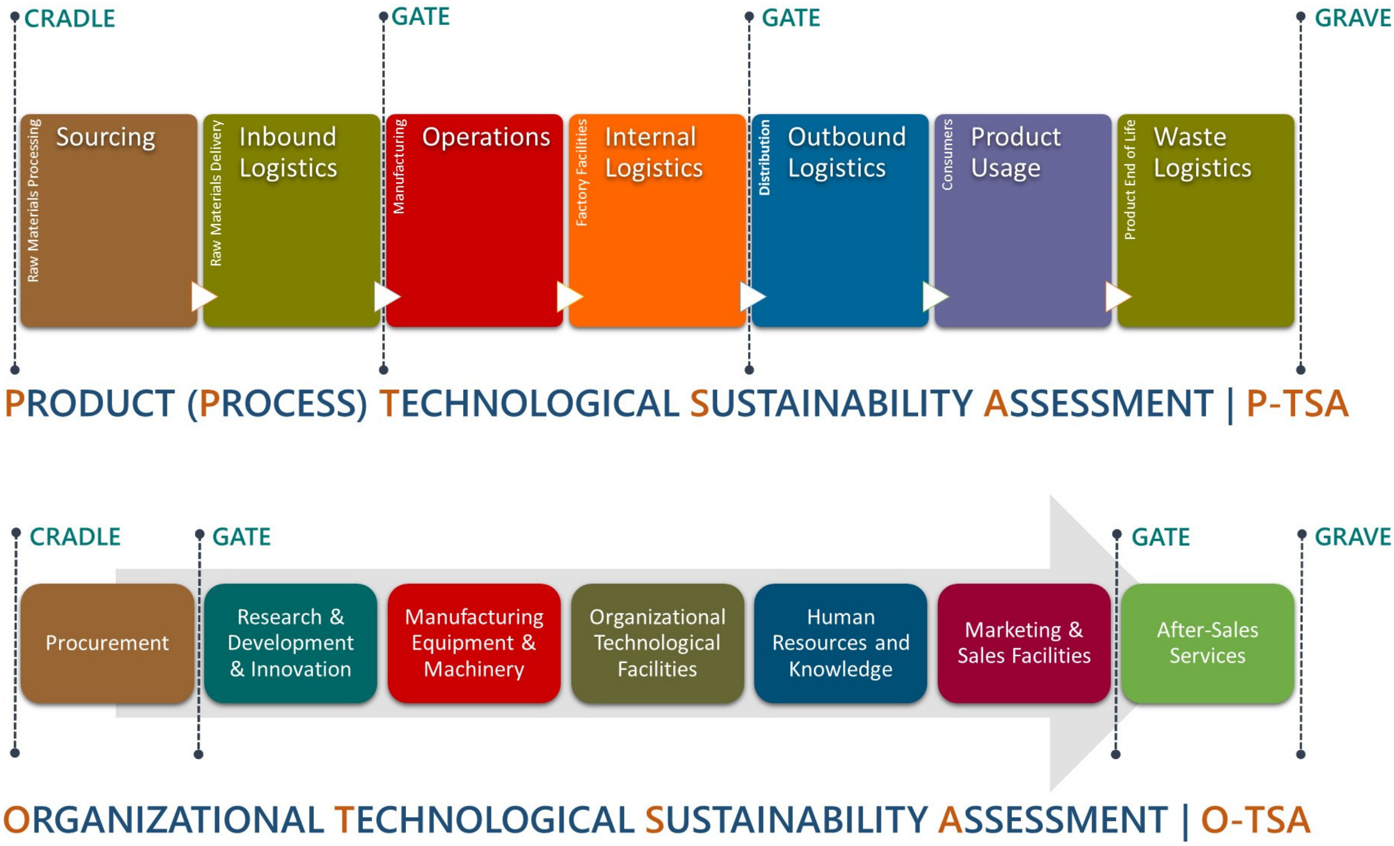

Figure 1. Life cycle approach to assessing product/process (P-TSA) and organizational (O-TSA) technological sustainability.

In the case of P-TSA, the following activities are addressed.

1. Sourcing (cradle-to-gate): supply of the raw materials and the other factors of productions.
2. Inbound Logistics (cradle-to-gate): delivery of raw materials and other inputs to the factory.
3. Operations (gate-to-gate): processes of physical and/or chemical transformation of production factors (inputs) into finished products (outputs) ready for sale, including packaging.
4. Internal Logistics (gate-to-gate): handling and storage of finished products awaiting shipment.
5. Outbound Logistics (gate-to-grave): processes of picking up products at the manufacturer's warehouse for delivery to the distributor or end customer.
6. Product Usage (gate-to-grave): these are the activities of using the product whether it is industrial assets for other industrial customers (business-to-business market) or consumer goods (business-to-consumer market).
7. Waste Logistics (gate-to-grave): product end-of-life and waste gathering and disposal.

In the case of the O-TSA, the perspective of the analysis changes to focus on the organization that controls the technologies to design, manufacture, and market a product. Following the same logic adopted previously, the main activities identified are as follows:

1. Procurement (cradle-to-gate): refers to the function of purchasing technological inputs such as raw materials, semi-finished goods, machinery, equipment, and services used by the organization.
2. Research and Development and Innovation (gate-to-gate): this is a strategic function of the organization that must build and preserve competitive advantage through product and process innovation both enabled by the development of new technologies and knowledge.
3. Manufacturing Equipment and Machinery (gate-to-gate): the endowment of innovative or, on the contrary, outdated manufacturing technologies has a significant impact on the company's competitiveness.
4. Organizational Technological Facilities (gate-to-gate): the relationship between technology and business organization goes beyond manufacturing operations and involves IT infrastructure, management systems such as Enterprise Resource Planning (ERP), and Business Intelligence systems (BI), all of which are essential tools for data collection and information processing.
5. Human Resources and Knowledge (gate-to-gate): human resources, both at the individual and organizational level, play a fundamental role in technological innovation processes. Knowledge represents the intangible component of an organization's technological assets, expressed through culture, skills, interactions between parties, and decision-making heuristics.
6. Marketing and Sales Facilities (gate-to-gate): technologies must be at the service of marketing and commercial strategies to integrate and automate data and information that are collected and processed in other departments (product development, production, management control, and administration and finance).
7. After-Sales Services (gate-to-grave): it means the set of assistance activities that a company provides to a customer before, during, and after the purchase or use of a consumable product and the technical support services of industrial companies that manufacture durable goods.

4.2. Technological Inventory Analysis

This phase includes all activities aimed at collecting data on all inputs and outputs included in the system boundary and elaborating specific technological metrics related to each category of activity of the product/process system (P-TSA) or organization (O-TSA) considered.

4.3. Technological Impact Assessment

According to ISO 14040, this is the third phase of the assessment, aiming to convert the inputs and outputs identified in the inventory analysis phase into potential contributions to technological life cycle impacts.

4.3.1. Selection of Technological Impact Categories

The selection of impact categories for technological sustainability assessment must be consistent with the objective and scope of the study and specify the technological concerns of interest to the organization. Therefore, starting with the explanatory hypothesis that sees technological sustainability as the ability of a production system to maintain its operational performance over time, the following impact categories were selected.

1. In-/Outputs Availability (IOA): Refers to the potential of the system to provide the necessary inputs and outputs at the appropriate time to ensure continuity of operations. The output of one phase or activity in the life cycle becomes the input of the next.
2. Operational Performance (OP): Describes the potential of the outputs of a process step or activity to meet the demands and needs of the organization's internal users or end customers, optimizing the ratio of output value to input use.
3. Technical Quality (TQ): Expresses the set of intrinsic characteristics and functional parameters that the output possesses and that satisfy the expected requirements of users and/or customers in accordance with current regulations.

More generally, the concepts of availability, performance, and quality are used to build the OEE (Overall Equipment Effectiveness) index used to monitor the production losses of an equipment or process [101]. In this case, availability measures production losses related to downtime, performance measures losses related to reduced speed, and quality measures losses due to units that are not released [102]. The choice of these parameters as technology impact categories is based on the results of the study by Durán and Durán [103] who, in addition to scaling the analysis from the facility to factory level, employ this approach to determine the systemic impact of each piece of equipment through a sensitivity analysis.

4.3.2. Classification

In this phase, the technological metrics selected earlier (Section 4.2), are associated with the various impact categories according to the effects they may have on the production performance of a manufacturing organization.

4.3.3. Characterization

In order to assess the technological sustainability, we create a composite index, namely a combination of individual indicators, which represents a convenient tool to convey information. The first stage of constructing a composite index is the selection of individual indicators.

For each impact category, technological metrics are used to create indicators. These indicators make it possible to quantitatively express the contribution provided by each technological metric to each impact category.

In the case of IOA, average stock and average consumption were selected as the technological metrics to construct the Stock Coverage Rate (SCR) indicator.

Let "A" be the set of organizational activities, so that each activity $a \in A$; and let "i_a" represent the input associated with each activity "a": $\forall a \in A \; \exists \, i_a$. The Stock Coverage Rate (SCR) for each input "i_a" can be defined as follows:

$$SCR^t_{i_a} = \frac{AS^t_{i_a}}{AC^t_{i_a}} \tag{1}$$

$SCR^t_{i_a}$ = Stock Coverage Rate of input i, in the activity a, at time t.
$AS^t_{i_a}$ = Average Stock of input i, in the activity a, at time t.
$AC^t_{i_a}$ = Average Consumption of input i, in the activity a, at time t.

As operations management aims to optimize the use of an organization's resources, productivity metrics are key to evaluating operations-related performance. Therefore, in the case of the OP, inputs and outputs have been adopted as technological metrics to construct the Productivity Indicator. Productivity is the ratio between the real output of the production and the resources really employed (input) to generate said output, representing the capability to rationally use resources.

$$PI^t_a = \frac{ROU^t_a}{RIN^t_a} \tag{2}$$

PI^t_a = Productivity Indicator of the activity a, at time t.
ROU^t_a = Real Output in the activity a, at time t.
RIN^t_a = Real Input in the activity a, at time t.

Finally, in the case of TQ, the technological metrics selected were the quality parameter controlled, and the acceptability threshold of this parameter set by current regulations to assign conformity to the output produced. The ratio between these two metrics represents the Output Conformity Rate (OCR).

Let "o_a" be the output generated from each activity "a", the OCR for each output "o_a" can be formalized as follows:

$$OCR^t_{o_a} = \frac{QP^t_{o_a}}{AT^t_{o_a}} \tag{3}$$

$OCR^t_{o_a}$ = Output Conformity Rate of output o, in the activity a, at time t.
$QP^t_{o_a}$ = Quality Parameter of output o, in the activity a, at time t.
$AT^t_{o_a}$ = Acceptability Threshold of output o, in the activity a, at time t.

4.3.4. Normalization and Aggregation

As individual indicators often have different scales of measurement, normalization is required prior to any aggregation [104]. This process brings indicators onto a common scale, maintaining the relative differences and producing dimensionless scores that allow for comparison.

For the purpose of the study, we opted for standardization (z-scores); for each individual indicator, the mean ($\overline{x}$) and the standard deviation (σ) across activities are computed.

Let K be a set of individual indicators $K = \{k_\mathrm{m}\}$, $m = 1, \ldots, M$, standard scores are derived as:

$$z^t_{ka} = \frac{x^t_{ka} - \overline{x}^t_k}{\sigma^t_k} \tag{4}$$

z^t_{ka} = standardized score of the indicator k, for activity a, at time t.
x^t_{ka} = score of the indicator k, for activity a, at time t.
$\overline{x}^t_k$ = average score of indicator k, for all activities, at time t.
σ^t_k = standard deviation of indicator k, for all activities, at time t.

After standardization, data will have a 0 mean and a unit standard deviation.

Next, the results of the impact categories are first multiplied by weighting factors and then added together to obtain a single value, thus allowing the assignment of values to the different impact categories.

Weights reflect the relative importance of each individual indicator to the overall composite index [105]. Given a set of individual indicators $K = \{k_m\}$, we can define the set of indicator weights as $W = \{w_m\}$, with $m = 1, \ldots, M$, such that $w_m \geq 0$ and $\sum_{m=1}^{M} w_m = 1$.

Because of the exploratory nature of the study, adopting the approach already followed in other studies [106], we assume equal weights for all indicators:

$$w_m = \frac{1}{M} \tag{5}$$

w_m = weight of indicator k_m.
M = total number of indicators for each activity a in the life cycle.

Weighted arithmetic mean, one of the most widely used aggregation methods [107], was used to aggregate normalized indicators and into sub-indexes for each category of technological impact.

$$IOAI^t = \sum_{a \in A} w_m (zSCR_{i_a})^t \tag{6}$$

$$OPI^t = \sum_{a \in A} w_m (zPI_a)^t \tag{7}$$

$$TQI^t = \sum_{a \in A} w_m (zOCR_{o_a})^t \tag{8}$$

$(IOAI)_t$ = In-/Output Availability Index for the standardized indicator $zSCR$, at time t.
$(OPI)_t$= Operational Performance Index for the standardized indicator zPI, at time t.
$(TQI)_t$ = Technical Quality Index for the standardized indicator $zOCR$, at time t.

Finally, to build the overall Technological Sustainability Index (TSI), we aggregate the scores obtained from partial indices (*IOAI*, *OPI*, and *TQI*), each of them corresponding to an impact category.

In particular, given the set of sub-indexes $H = \{h_j\}$ ($j = 1, \ldots, J$), we assign to each sub-index "h_j" a weight '$w_j \geq 0$', such that $\sum_{j=1}^{J} w_j = 1$. The composite index can be formalized as follows:

$$TSI^t = \sum_{j=1}^{J} w_j \, h_j^t \tag{9}$$

$$TSI^t = \left[w_{IOA}\; IOAI^t\right] + \left[w_{OP}\; OPI^t\right] + \left[w_{TQ}\; TQI^t\right] \tag{10}$$

Additionally, in this case an equal weighting scheme was adopted, as the three dimensions have equal status in the composite index. However, weighting factors may be set differently depending on the relevance attributed by the organization to individual indicators.

We can now take into consideration the TSI time series for year t, which can be expressed as:

$$TSI_1^t,\; TSI_2^t, \ldots, TSI_{12}^t \tag{11}$$

Then, let us consider the *TSI* time series for the previous year $t - 1$:

$$TSI_1^{t-1},\; TSI_2^{t-1}, \ldots, TSI_{12}^{t-1} \tag{12}$$

The use of time series, as demonstrated by other studies [108,109], allows for the analysis of trends in the performance of an index. The trend variance rate of technological sustainability ($\Delta TSI_{t-1,t}$) is then given by the ratio between the index of the month of reference at time "t" and that of the corresponding month at time 't – 1', the result is multiplied by 100 and then 100 is subtracted. For example, considering the month of March for year t and year $t - 1$, the following will occur:

$$\Delta TSI_{t-1,t} = \left(\frac{TSI_3^t}{TSI_3^{t-1}} \cdot 100\right) - 100 \tag{13}$$

This trend variance rate provides additional information about the effects of technology on process, product, and organization because it includes the time dimension. The performance achieved in transforming inputs into outputs using technology in operational activities can be monitored with the IOA, OP, and TQ indexes. While the evaluation of the technology-driven change can be measured as the result (outcome) generated by the product or process (output) and the impact (positive or negative) that the result has induced on the organization in the medium to long term (Figure 2). Outcome and impact, if positive, can be seen as benefits for the consumers of the products and for the organization that has operated the manufacturing process. Or, in other words, as the value generated by the organization for stakeholders when their expectations are met. One way to capture the contribution made by technology to value creation may be to perform a simple arithmetic mean of the monthly trend variance rates to obtain the Technology Improvement Index (TII) (Equation (14)).

$$TII_{t-1,t} = \frac{\sum_{1}^{12} \Delta TSI_{t-1,t}}{12} \tag{14}$$

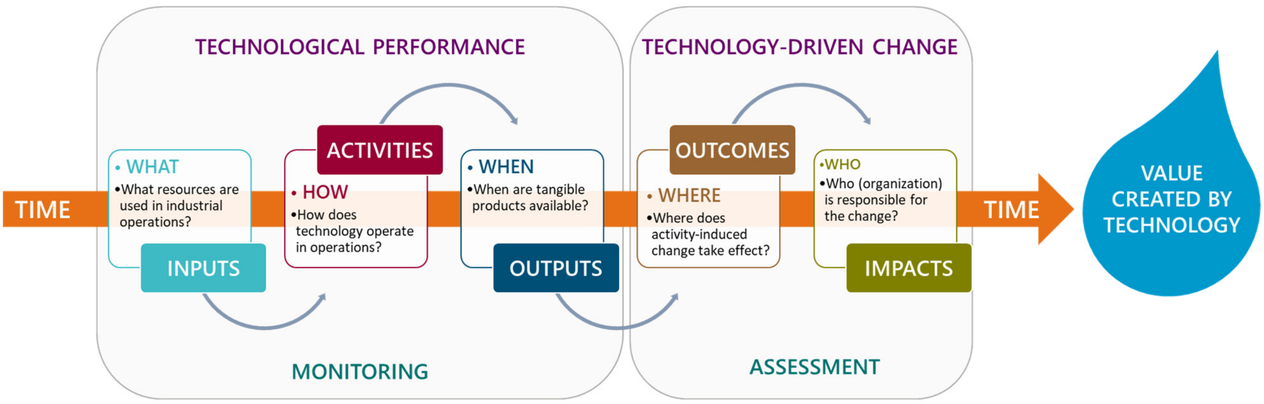

Figure 2. Causal relationships between inputs, activities, outputs, outcomes, and impacts in the chain of change to create value by technology.

This index provides an indication of how the organization, in processing resources to obtain products, improves (or worsens) its results and impacts as a result of technology, from one year to the next. The economic and social value created through technological improvement can be quantified by integrating this assessment with the socio-economic and environmental ones.

4.4. Technological Interpretation

Whatever output/outcome of the data collection and processing procedures, it requires the researcher to perform interpretation, i.e., to attribute meaning and technological value to the intermediate or final results of the sustainability assessment. Therefore, interpretation is the stage of the technological sustainability assessment in which the results obtained in the inventory analysis and impact assessment are combined in a manner consistent with the objectives and scope of the study to derive insights and recommendations. Any critical issues identified in the impact assessment can help to modify processes, products, and organizational procedures in an iterative approach to improvement. Interpretation should contain three main activities: (1) identification of significant factors that have the potential to change the final results of the technology assessment; (2) evaluation of the completeness of the inventory and impact assessment supplemented with sensitivity analysis of key factors for technology impact and checking for consistency of methods and data with the objective and scope; (3) preparation of a final report that includes the results obtained and the conclusions reached with the study.

This procedure, although subdivided into phases, should be conducted with an overview as schematized in Figure 3 for the P-TSA and O-TSA respectively. In fact, results are not automatically endowed with meaning if the researcher does not combine his expertise in processing technical data, with a technological sensitivity derived from knowledge of the organizational context of application of the results and his interpretive effort. Interpretation requires the rhetorical ability to argue the choices made and to effectively interpret and expose the key findings, thanks to the two-way contamination between technological data and organizational context. The stronger this relationship, the higher the heuristic potential of the final Technology Sustainability Indexes (P-TSI and O-TSI).

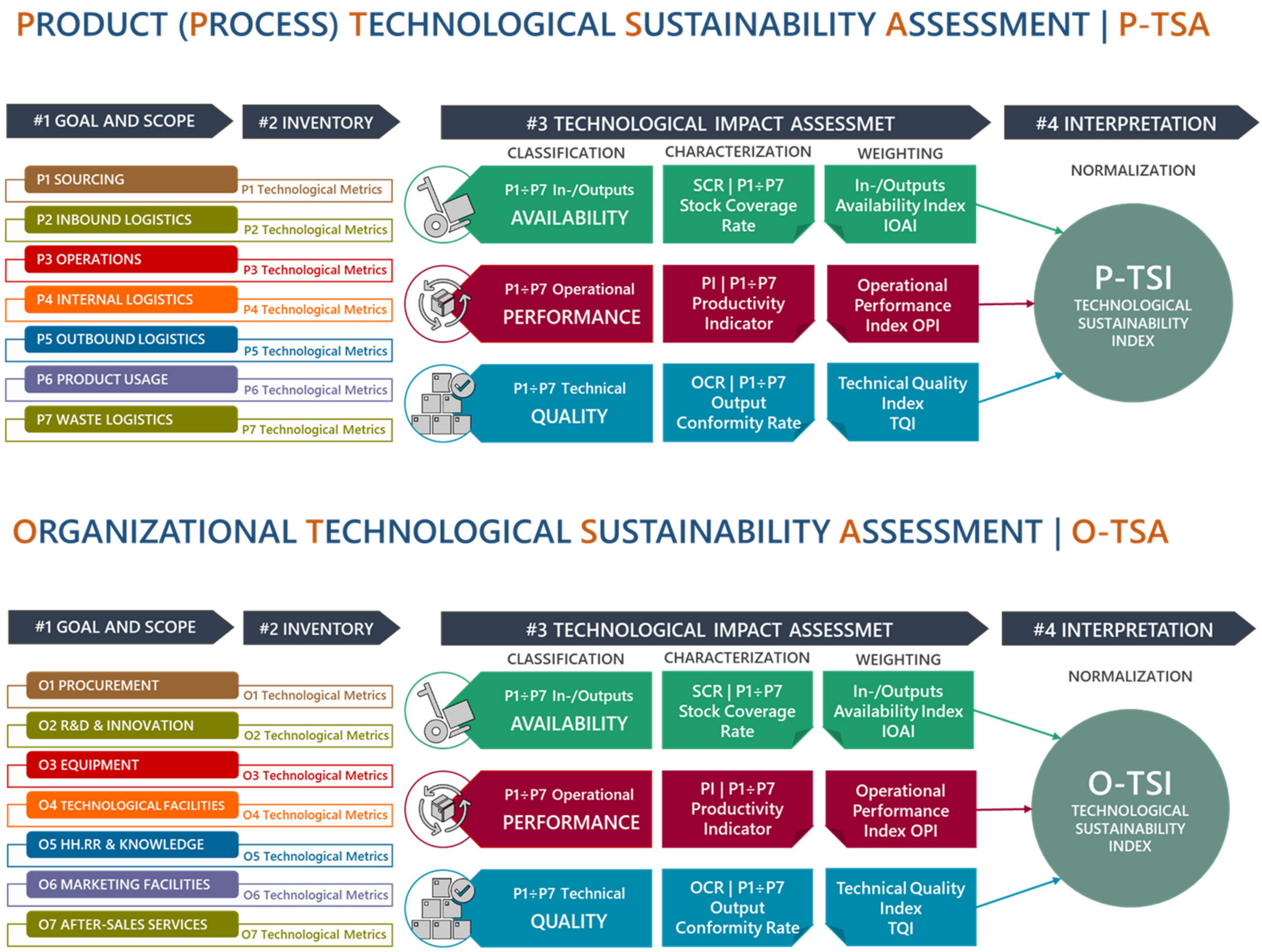

Figure 3. Holistic interpretive frameworks for the four phases of both product/process (P-TSA) and organizational (O-TSA) technology sustainability assessment. The frameworks differ for the different activities considered in phase #1 and #2.

5. Discussion of Results

Following a theoretical-conceptual perspective, the main result of this research is a methodological framework for technological sustainability assessment (TSA) based on the life cycle approach (LCT) and in line with the operational scheme of ISO 14040. The methodological framework is divided into two application options: one to determine the technological sustainability of a product or process (P-TSA) and the other designed for a whole manufacturing organization (P-TSA). In both cases, to adopt the perspective of the value chain and the life cycle approach (cradle-to-gate and gate-to-grave), seven main activities have been identified against which to conduct the analysis of technological sustainability. In addition, three impact categories necessary to determine the level of technology impact along the value chain were defined for both: In-/Outputs Availability (IOA), Operational Performance (OP), and Technical Quality (TQ).

By combining a set of technology metrics, three general indicators were defined for each impact category: Stock Coverage Rate indicator (SCR), Productivity Indicator (PI), and Output Conformity Rate (OCR). When applying this technology sustainability assessment framework, analysts should appropriately select those specific metrics that best represent the impact of technology on their product/process or organization.

After weighting, the indicators for each impact category can be aggregated into general indices of technological impact: In-/Outputs Availability Index (IOAI), Operational Performance Index (OPI), and Technical Quality Index (TQI). Finally, a mathematical way to construct the Technological Sustainability Index (TSI) was provided. This index quantitatively describes the degree of technological sustainability associated with the product/process or, more generally, the level of technological sustainability achieved by the organization.

Finally, in order to capture the trend of technological sustainability over time, the methodological framework also proposes to normalize the indices measured at a given time with respect to an internal baseline, obtaining a further index called Technology Improvement Index (TII). This has the advantage of including the dimension of time in the assessment of technological sustainability, showing how technology contributes to improving the performances of a product/process or the outcomes of an organization. The economic and social value created through technological improvement can be quantified by integrating this assessment with the socio-economic and environmental ones.

The results obtained from this conceptual framing provide several implications for both scholars as well as practitioners and businesses.

5.1. Implications to Academia

This paper contributes to fill the gap in the literature regarding the concept of technological sustainability, which is often instead understood as the sustainability of technological solutions. Thus, technology becomes an integral part of sustainability along with environment, economy, and society, providing a multidimensional view of it. To justify this new attribution of meaning, three categories of technological impact have been identified (In-/Outputs Availability; Operational Performance; Technical Quality), all of which are necessary to determine whether a production system is able to maintain its functional capabilities over time. For each impact category, an index is determined by combining specific technology indicators and metrics. This study therefore provides a methodological framework for quantifying, with a general technology sustainability index, the contribution made by technology to the value creation of an organization (O-TSI) through a product or process (P-TSI).

5.2. Implications to Practitioners

From the perspective of industrial and business practitioners, the framework for assessing sustainability technology provides a promising operational tool for monitoring how technologies really contribute to the effectiveness of production systems. Normally, industrial engineering and operations research specialists focus on analyzing the performance efficiency of a single piece of equipment. In contrast, the technology assessment framework proposed in this study, with its holistic view, shifts the focus of managers from the nano-level of machinery to the micro level of the whole system, up to the meso level of the supply chain, expanding the possibilities for broadening knowledge about the real contribution of processes, products, and organization to value creation.

5.3. Limitations and Future Research Directions

Due to its theoretical-conceptual focus, this paper has some limitations that nevertheless offer insights for subsequent in-depth research activities. First, the proposed technological sustainability assessment framework will need to be validated through its application in an operational context. In fact, it is necessary to ascertain that the indicators and indices, as well as the technological impact categories, are relevant and suitable for different production environments. Second, if the empirical validation is successful, it will be necessary to reinforce the theoretical construction that, while having a certain degree of detail, needs to be linked to current management theories in order to make the introduction of an additional pillar of sustainability more solid. Finally, it is necessary to explore the relationships between technological sustainability, introduced in this study, and environmental, social, and economic sustainability, in order to build an integrated framework of sustainable development.

6. Conclusions

The capability to equilibrate social, economic, and environmental sustainability is the essence of the concept of sustainable development, which has also become a key issue for manufacturing companies. This process ensures a balance between the economic growth of a given industry, care for the environment and the well-being of the society in which it is integrated. Cross-cutting each of these concepts is technology as a fundamental element both in industrial processes and in every aspect of people's lives. In every era of human history, technological innovations have arisen that can optimize processes and advance societies, so it is necessary to think of technology as an enabler for sustainability.

In this paper, the authors aimed to investigate the transversal character of technology with respect to the environmental, economic, and social dimensions of sustainability in order to highlight its relevance for preserving the equilibrium between the three pillars of sustainable development. The theoretical construction was grounded in the definitions of sustainability and sustainable production and on the methodological approach of Life Cycle Thinking (LCT). Under conceptual abstraction, and applying an abductive inference, it was assumed the existence of technological sustainability understood as the capability of a production system to maintain its operational performance.

Thanks to these theoretical backgrounds, it was possible to answer positively the RQ1 stated in the introduction, that is, technology can be seen as a key dimension of sustainability along with environment, economy, and society. Then, following the holistic view of Life Cycle Thinking and the methodological scheme of ISO 14040, a framework was proposed to carry out the assessment of the technological sustainability of an organization (O-TSA) and of a product or process (P-TSA). This provided a positive response to RQ2.

This research represents an initial conceptual and exploratory contribution aimed at providing an operational framework to help manufacturing companies to consider the technological dimension within the broader framework of the sustainability of a product/process and an organization.

Author Contributions: Conceptualization, M.V. and D.S.-B.; investigation, M.V.; methodology, D.S.-B.; validation, C.S.; supervision, C.S.; data curation, F.D.; resources, E.I.C.-G.; formal analysis, R.G.-S.; writing—original draft preparation, D.S.-B.; writing—review and editing, M.V. All authors have read and agreed to the published version of the manuscript.

Funding: This research was co-funded by the European Union under the LIFE Program, grant number: LIFE16ENV/IT/000307 (LIFE Force of the Future).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Kao, Y.S.; Nawata, K.; Huang, C.Y. Systemic functions evaluation based technological innovation system for the sustainability of IoT in the manufacturing industry. *Sustainability* **2019**, *11*, 2342. [CrossRef]
2. Yang, Z.; Sun, J.; Zhang, Y.; Wang, Y. Green, green, it's green: A triad model of technology, culture, and innovation for corporate sustainability. *Sustainability* **2017**, *9*, 1369. [CrossRef]
3. García-Granero, E.M.; Piedra-Muñoz, L.; Galdeano-Gómez, E. Measuring eco-innovation dimensions: The role of environmental corporate culture and commercial orientation. *Res. Policy* **2020**, *49*, 104028. [CrossRef]
4. Macchi, M.; Savino, M.; Roda, I. Analysing the support of sustainability within the manufacturing strategy through multiple perspectives of different business functions. *J. Clean. Prod.* **2020**, *258*, 120771. [CrossRef]
5. Brink, M.; Hengeveld, G.M.; Tobi, H. Interdisciplinary measurement: A systematic review of the case of sustainability. *Ecol. Indic.* **2020**, *112*, 106145. [CrossRef]
6. Abdul-Rashid, S.H.; Sakundarini, N.; Raja Ghazilla, R.A.; Thurasamy, R. The impact of sustainable manufacturing practices on sustainability performance: Empirical evidence from Malaysia. *Int. J. Oper. Prod. Manag.* **2017**, *37*, 182–204. [CrossRef]
7. Bag, S.; Yadav, G.; Dhamija, P.; Kataria, K.K. Key resources for industry 4.0 adoption and its effect on sustainable production and circular economy: An empirical study. *J. Clean. Prod.* **2021**, *281*, 125233. [CrossRef]
8. Ferrari, A.M.; Volpi, L.; Settembre-Blundo, D.; García-Muiña, F.E. Dynamic life cycle assessment (LCA) integrating life cycle inventory (LCI) and Enterprise resource planning (ERP) in an industry 4.0 environment. *J. Clean. Prod.* **2021**, *286*, 125314. [CrossRef]
9. Bai, C.; Dallasega, P.; Orzes, G.; Sarkis, J. Industry 4.0 technologies assessment: A sustainability perspective. *Int. J. Prod. Econ.* **2020**, *229*, 107776. [CrossRef]
10. Miceli, A.; Hagen, B.; Riccardi, M.P.; Sotti, F.; Settembre-Blundo, D. Thriving, not just surviving in changing times: How sustainability, agility and digitalization intertwine with organizational resilience. *Sustainability* **2021**, *13*, 2052. [CrossRef]
11. Saad, M.H.; Darras, B.M.; Nazzal, M.A. Evaluation of Welding Processes Based on Multi-dimensional Sustainability Assessment Model. *Int. J. Precis. Eng. Manuf.-Green Technol.* **2021**, *8*, 57–75. [CrossRef]
12. Osorio, L.A.R.; Lobato, M.O.; Del Castillo, X.Á. Debates on sustainable development: Towards a holistic view of reality. *Environ. Dev. Sustain.* **2005**, *7*, 501–518. [CrossRef]
13. Rodríguez, R.; Svensson, G.; Wood, G. Determining corporate direction in sustainable development: A multi-dimensional framework in B2B. *J. Bus. Ind. Mark.* **2021**, *36*, 1–17. [CrossRef]
14. Purvis, B.; Mao, Y.; Robinson, D. Three pillars of sustainability: In search of conceptual origins. *Sustain. Sci.* **2019**, *14*, 681–695. [CrossRef]
15. Braccini, A.M.; Margherita, E.G. Exploring organizational sustainability of Industry 4.0 under the triple bottom line: The case of a manufacturing company. *Sustainability* **2018**, *11*, 36. [CrossRef]
16. Akbari, M.; Khodayari, M.; Danesh, M.; Davari, A.; Padash, H. A bibliometric study of sustainable technology research. *Cogent Bus. Manag.* **2020**, *7*. [CrossRef]
17. Feroz, A.K.; Zo, H.; Chiravuri, A. Digital transformation and environmental sustainability: A review and research agenda. *Sustainability* **2021**, *13*, 1530. [CrossRef]
18. Oláh, J.; Aburumman, N.; Popp, J.; Khan, M.A.; Haddad, H.; Kitukutha, N. Impact of industry 4.0 on environmental sustainability. *Sustainability* **2020**, *12*, 4674. [CrossRef]
19. Malek, J.; Desai, T.N. A systematic literature review to map literature focus of sustainable manufacturing. *J. Clean. Prod.* **2020**, *256*, 120345. [CrossRef]
20. Karuppiah, K.; Sankaranarayanan, B.; Ali, S.M.; Chowdhury, P.; Paul, S.K. An integrated approach to modeling the barriers in implementing green manufacturing practices in SMEs. *J. Clean. Prod.* **2020**, *265*, 121737. [CrossRef]
21. Bhanot, N.; Qaiser, F.H.; Alkahtani, M.; Rehman, A.U. An integrated decision-making approach for cause-and-effect analysis of sustainable manufacturing indicators. *Sustainability* **2020**, *12*, 1517. [CrossRef]
22. Enyoghasi, C.; Badurdeen, F. Industry 4.0 for sustainable manufacturing: Opportunities at the product, process, and system levels. *Resour. Conserv. Recycl.* **2021**, *166*, 105362. [CrossRef]
23. Machado, C.G.; Winroth, M.P.; Ribeiro da Silva, E.H.D. Sustainable manufacturing in Industry 4.0: An emerging research agenda. *Int. J. Prod. Res.* **2020**, *58*, 1462–1484. [CrossRef]
24. Esmaeel, R.I.; Zakuan, N.; Jamal, N.M.; Taherdoost, H. Understanding of business performance from the perspective of manufacturing strategies: Fit manufacturing and overall equipment effectiveness. In Proceedings of the Procedia Manufacturing, Tirgu Mures, Romania, 5–6 October 2017; Elsevier: Amsterdam, The Netherlands, 2018; Volume 22, pp. 998–1006.
25. Uhlemann, J.; Costa, R.; Charpentier, J.C. Product design and engineering—Past, present, future trends in teaching, research and practices: Academic and industry points of view. *Curr. Opin. Chem. Eng.* **2020**, *27*, 10–21. [CrossRef]
26. Mehr, R.; Lüder, A. Managing Complexity Within the Engineering of Product and Production Systems. In *Security and Quality in Cyber-Physical Systems Engineering*; Springer: Cham, Switzerland, 2019; pp. 57–79.

27. Etienne, A.; Mirdamadi, S.; Mohammadi, M.; Babaeizadeh Malmiry, R.; Antoine, J.F.; Siadat, A.; Dantan, J.Y.; Tavakkoli, R.; Martin, P. Cost engineering for variation management during the product and process development. *Int. J. Interact. Des. Manuf.* **2017**, *11*, 289–300. [CrossRef]
28. Šatanová, A.; Závadský, J.; Sedliačiková, M.; Potkány, M.; Závadská, Z.; Holíková, M. How Slovak small and medium manufacturing enterprises maintain quality costs: An empirical study and proposal for a suitable model. *Total Qual. Manag. Bus. Excell.* **2015**, *26*, 1146–1160. [CrossRef]
29. Miklosik, A.; Starchon, P.; Hitka, M. Environmental sustainability disclosures in annual reports of ASX Industrials List companies. *Environ. Dev. Sustain.* **2021**, 1–19. [CrossRef]
30. Clementino, E.; Perkins, R. How Do Companies Respond to Environmental, Social and Governance (ESG) ratings? Evidence from Italy. *J. Bus. Ethics* **2021**, *171*, 379–397. [CrossRef]
31. Marsiglio, S.; Privileggi, F. On the economic growth and environmental trade-off: A multi-objective analysis. *Ann. Oper. Res.* **2021**, *296*, 263–289. [CrossRef]
32. Fracarolli Nunes, M.; Lee Park, C.; Paiva, E.L. Can we have it all? Sustainability trade-offs and cross-insurance mechanisms in supply chains. *Int. J. Oper. Prod. Manag.* **2020**, *40*, 1339–1366. [CrossRef]
33. De la Porte, C.; Jensen, M.D. The next generation EU: An analysis of the dimensions of conflict behind the deal. *Soc. Policy Adm.* **2021**, *55*, 388–402. [CrossRef]
34. García-Muiña, F.E.; Medina-Salgado, M.S.; Ferrari, A.M.; Cucchi, M. Sustainability transition in industry 4.0 and smart manufacturing with the triple-layered business model canvas. *Sustainability* **2020**, *12*, 2364. [CrossRef]
35. Gissi, E.; Gaglio, M.; Aschonitis, V.G.; Fano, E.A.; Reho, M. Soil-related ecosystem services trade-off analysis for sustainable biodiesel production. *Biomass Bioenergy* **2018**, *114*, 83–99. [CrossRef]
36. Kono, J.; Ostermeyer, Y.; Wallbaum, H. Trade-offbetween the social and environmental performance of green concrete: The case of 6 countries. *Sustainability* **2018**, *10*, 2309. [CrossRef]
37. Kozlova, E.P.; Kuznetsov, V.P.; Garina, E.P.; Romanovskaya, E.V.; Andryashina, N.S. Methodological Bases of the Assessment of Sustainable Development of Industrial Enterprises (Technological Approach). In *The 21st Century from the Positions of Modern Science: Intellectual, Digital and Innovative Aspects*; Springer: Cham, Switzerlna, 2020; Volume 91, pp. 670–679.
38. Petry, M.; Köhler, C.; Zhang, H. Interaction analysis for dynamic sustainability assessment of manufacturing systems. *Procedia CIRP 90*, 477–482. [CrossRef]
39. Al-Shoqran, M.; Al Zub'i, S. A Review on Industry 4.0 Management for Sustainable Technologies. In Proceedings of the Lecture Notes in Networks and Systems, EAMMINS 2021, Istanbul, Turkey, 19–20 March 2021; Springer: Cham, Switzerland, 2021; Volume 239 LNNS, pp. 206–217.
40. Amato, V. *The Sustainable Development Goals: A Framework for Business*; Springer: Cham, Switzerland, 2021; pp. 21–40.
41. Jun, S. Bayesian count data modeling for finding technological sustainability. *Sustainability* **2018**, *10*, 3220. [CrossRef]
42. Sadriddinov, M.I.; Mezina, T.V.; Morkovkin, D.E.; Romanova, J.A.; Gibadullin, A.A. Assessment of technological development and economic sustainability of domestic industry in modern conditions. *IOP Conf. Ser. Mater. Sci. Eng.* **2020**, *734*, 012051. [CrossRef]
43. Bolla, R.; Bruschi, R.; Davoli, F.; Lombardo, C.; Pajo, J.F.; Sanchez, O.R. The dark side of network functions virtualization: A perspective on the technological sustainability. In Proceedings of the IEEE International Conference on Communications, Paris, France, 21–25 May 2017.
44. Dewulf, J.; Van Langenhove, H.; Mulder, J.; Van Den Berg, M.M.D.; Van Der Kooi, H.J.; De Swaan Arons, J. Illustrations towards quantifying the sustainability of technology. *Green Chem.* **2000**, *2*, 108–114. [CrossRef]
45. Coskun-Setirek, A.; Tanrikulu, Z. Technological Sustainability of Mobile Learning. *Online J. Sci. Technol.* **2017**, *7*, 89–97.
46. Mendes, R.P.; Gonçalves, L.C.; Gaspar, P.D. Contribution for a better understanding of the technological sustainability in electrical energy production through photovoltaic cells. *Renew. Energy Power Qual. J.* **2010**, *1*, 824–828. [CrossRef]
47. Gopalakrishnan, S. Technological Sustainability and Green Libraries: A Study among Library Professionals Working in Select Higher Education Institutions In and Around Chennai. *J. Adv. Libr. Inf. Sci.* **2016**, *5*, 1–11.
48. Weaver, P.; Jansen, L.; van Grootveld, G.; van Spiegel, E.; Vergragt, P. *Sustainable Technology Development*; Routledge: London, UK, 2017; ISBN 9781351283243.
49. De-Pablos-Heredero, C.; Montes-Botella, J.L.; García-Martínez, A. Sustainability in smart farms: Its impact on performance. *Sustainability* **2018**, *10*, 1713. [CrossRef]
50. Udo, V.E.; Jansson, P.M. Bridging the gaps for global sustainable development: A quantitative analysis. *J. Environ. Manag.* **2009**, *90*, 3700–3707. [CrossRef] [PubMed]
51. Kim, J.M.; Sun, B.; Jun, S. Sustainable technology analysis using data envelopment analysis and state space models. *Sustainability* **2019**, *11*, 3597. [CrossRef]
52. Silva, R.M.; Silva, A.R.C.; Lima, T.M.; Charrua-Santos, F.; Osório, G.J. Energy Sustainability Universal Index (ESUI): A proposed framework applied to the decision-making evaluation in power system generation. *J. Clean. Prod.* **2020**, *275*, 124167. [CrossRef]
53. Yakovleva, E.; Miller, A. Technological sustainability of industrial enterprises in intellectual infrastructure theory framework. In Proceedings of the E3S Web of Conferences, Chelyabinsk, Russia, 17–19 February 2021; Kankhva, V., Ed.; EDP Sciences: Ulis, France, 2021; Volume 258, p. 06012.

54. Adom, D.; Attah, A.Y.; Ankrah, K. Constructivism philosophical paradigm: Implication for research, teaching and learning. *Glob. J. Arts Humanit. Soc. Sci.* **2016**, *4*, 1–9.
55. Chiffi, D.; Pietarinen, A.V. Abductive inference within a pragmatic framework. *Synthese* **2020**, *197*, 2507–2523. [CrossRef]
56. Mathieu, J.E. The problem with [in] management theory. *J. Organ. Behav.* **2016**, *37*, 1132–1141. [CrossRef]
57. Philipsen, K. Theory building: Using abductive search strategies. In *Collaborative Research Design: Working with Business for Meaningful Findings*; Springer: Singapore, 2017; pp. 45–71, ISBN 9789811050084.
58. Dorsey, J.W.; Hardy, L.C. Sustainability factors in dynamical systems modeling: Simulating the non-linear aspects of multiple equilibria. *Ecol. Modell.* **2018**, *368*, 69–77. [CrossRef]
59. Kovacs, E.; Hoaghia, M.A.; Senila, L.; Scurtu, D.A.; Dumitras, D.E.; Roman, C. Sustainability problematization and modeling opportunities. *Sustainability* **2020**, *12*, 46. [CrossRef]
60. Jabłónski, A.; Jabłónski, M. Research on business models in their life cycle. *Sustainability* **2016**, *8*, 430. [CrossRef]
61. Ben-Eli, M.U. Sustainability: Definition and five core principles, a systems perspective. *Sustain. Sci.* **2018**, *13*, 1337–1343. [CrossRef]
62. Franciosi, C.; Voisin, A.; Miranda, S.; Riemma, S.; Iung, B. Measuring maintenance impacts on sustainability of manufacturing industries: From a systematic literature review to a framework proposal. *J. Clean. Prod.* **2020**, *260*, 121065. [CrossRef]
63. Ocampo, L.; Deiparine, C.B.; Go, A.L. Mapping Strategy to Best Practices for Sustainable Food Manufacturing Using Fuzzy DEMATEL-ANP-TOPSIS. *EMJ Eng. Manag. J.* **2020**, *32*, 130–150. [CrossRef]
64. Ordieres-Meré, J.; Remón, T.P.; Rubio, J. Digitalization: An opportunity for contributing to sustainability from knowledge creation. *Sustainability* **2020**, *12*, 1460. [CrossRef]
65. Garcia-Muiña, F.E.; González-Sánchez, R.; Ferrari, A.M.; Volpi, L.; Pini, M.; Siligardi, C.; Settembre-Blundo, D. Identifying the equilibrium point between sustainability goals and circular economy practices in an Industry 4.0 manufacturing context using eco-design. *Soc. Sci.* **2019**, *8*, 241. [CrossRef]
66. Omelchenko, I.; Drogovoz, P.; Gorlacheva, E.; Shiboldenkov, V.; Yusufova, O. The modeling of the efficiency in the new generation manufacturing-distributive systems based on the cognitive production factors. *IOP Conf. Ser. Mater. Sci. Eng.* **2019**, *630*, 012020. [CrossRef]
67. De Oliveira Neto, G.C.; Pinto, L.F.R.; Amorim, M.P.C.; Giannetti, B.F.; Almeida, C.M.V.B. de A framework of actions for strong sustainability. *J. Clean. Prod.* **2018**, *196*, 1629–1643. [CrossRef]
68. Bjorn, A.; Chandrakumar, C.; Boulay, A.M.; Doka, G.; Fang, K.; Gondran, N.; Hauschild, M.Z.; Kerkhof, A.; King, H.; Margni, M.; et al. Review of life-cycle based methods for absolute environmental sustainability assessment and their applications. *Environ. Res. Lett.* **2020**, *15*, 083001. [CrossRef]
69. Huertas-Valdivia, I.; Ferrari, A.M.; Settembre-Blundo, D.; García-Muiña, F.E. Social life-cycle assessment: A review by bibliometric analysis. *Sustainability* **2020**, *12*, 6211. [CrossRef]
70. Silk, D.; Mazzali, B.; Gargalo, C.L.; Pinelo, M.; Udugama, I.A.; Mansouri, S.S. A decision-support framework for techno-economic-sustainability assessment of resource recovery alternatives. *J. Clean. Prod.* **2020**, *266*, 121854. [CrossRef]
71. Eslami, Y.; Lezoche, M.; Panetto, H.; Dassisti, M. On analysing sustainability assessment in manufacturing organisations: A survey. *Int. J. Prod. Res.* **2021**, *59*, 4108–4139. [CrossRef]
72. Verma, V.; Jain, J.K.; Agrawal, R. Sustainability Assessment of Organization Performance: A Review and Case Study. In *Operations Management and Systems Engineering*; Springer: Singapore, 2021; pp. 205–219.
73. Toniolo, S.; Tosato, R.C.; Gambaro, F.; Ren, J. Life cycle thinking tools: Life cycle assessment, life cycle costing and social life cycle assessment. *Life Cycle Sustain. Assess. Decis. Methodol. Case Stud.* **2020**, 39–56. [CrossRef]
74. Obrecht, M. Integrating Life Cycle Thinking, Ecolabels and Ecodesign Principles into Supply Chain Management. In *Integration of Information Flow for Greening Supply Chain Management*; Springer: Cham, Switzerland, 2020; pp. 219–249.
75. Mazzi, A. Introduction. Life cycle thinking. In *Life Cycle Sustainability Assessment for Decision-Making: Methodologies and Case Studies*; Elsevier: Amsterdam, The Netherlands, 2020; ISBN 9780128183557.
76. Cai, W.; Lai, K. hung Sustainability assessment of mechanical manufacturing systems in the industrial sector. *Renew. Sustain. Energy Rev.* **2021**, *135*, 110169. [CrossRef]
77. Saxena, P.; Stavropoulos, P.; Kechagias, J.; Salonitis, K. Sustainability assessment for manufacturing operations. *Energies* **2020**, *13*, 2730. [CrossRef]
78. Sala, S.; Farioli, F.; Zamagni, A. Life cycle sustainability assessment in the context of sustainability science progress (part 2). *Int. J. Life Cycle Assess.* **2013**, *18*, 1686–1697. [CrossRef]
79. International Organization for Standardization. *ISO/IEC 14044: 2006 Environmental Management—Life Cycle Assessment—Requirements and Guidelines*; International Organization for Standardization: Geneva, Switzerland, 2006.
80. International Organization for Standardization. *ISO 15686-5: 2017(E)-Buildings and Constructed Assets—Service Life Planning*; International Organization for Standardization: Geneva, Switzerland, 2017.
81. Achten, W.; Barbeau-Baril, J.; Barros Telles Do Carmo, B.; Bolt, P.; Chandola, V.; Corona Bellostas, B.; Dadhish, Y.; Di Eusanio, M.; Di Cesare, S.; Di Noi, C.; et al. Guidelines for social life cycle assessment of products and organizations. *Guidel. Soc. Life Cycle Assess. Prod. Organ.* **2020**, *138*. Available online: https://www.lifecycleinitiative.org/wp-content/uploads/2021/01/Guidelines-for-Social-Life-Cycle-Assessment-of-Products-and-Organizations-2020-22.1.21sml.pdf (accessed on 3 September 2021).

82. López, N.M.; Santolaya Saénz, J.L.; Biedermann, A.; Sánchez-Migallón, J.M. Sustainability Assessment in the Implementation Phase of a Retail Space. In *Lecture Notes in Mechanical Engineering*; Springer: Cham, Switzerland, 2020; pp. 31–39.
83. Marzouk, M.; Azab, S. Environmental and economic impact assessment of construction and demolition waste disposal using system dynamics. *Resour. Conserv. Recycl.* **2014**, *82*, 41–49. [CrossRef]
84. Mohaddes Khorassani, S.; Ferrari, A.M.; Pini, M.; Settembre Blundo, D.; García Muiña, F.E.; García, J.F. Environmental and social impact assessment of cultural heritage restoration and its application to the Uncastillo Fortress. *Int. J. Life Cycle Assess.* **2019**, *24*, 1297–1318. [CrossRef]
85. Mahbub, N.; Oyedun, A.O.; Zhang, H.; Kumar, A.; Poganietz, W.R. A life cycle sustainability assessment (LCSA) of oxymethylene ether as a diesel additive produced from forest biomass. *Int. J. Life Cycle Assess.* **2019**, *24*, 881–899. [CrossRef]
86. Rosenbaum, R.K.; Hauschild, M.Z.; Boulay, A.M.; Fantke, P.; Laurent, A.; Núñez, M.; Vieira, M. Life cycle impact assessment. In *Life Cycle Assessment: Theory and Practice*; Springer: Cham, Switzerland, 2017; pp. 167–270, ISBN 9783319564753.
87. Wu, Y.; Su, D. Review of Life Cycle Impact Assessment (LCIA) Methods and Inventory Databases. In *Sustainable Product Development*; Springer Nature Switzerland AG: Cham, Switzerland, 2020; pp. 39–55.
88. Chen, X.; Matthews, H.S.; Griffin, W.M. Uncertainty caused by life cycle impact assessment methods: Case studies in process-based LCI databases. *Resour. Conserv. Recycl.* **2021**, *172*, 105678. [CrossRef]
89. Adams, C.A. Sustainability Reporting and Value Creation. *Soc. Environ. Account. J.* **2020**, *40*, 191–197. [CrossRef]
90. Gianni, M.; Gotzamani, K.; Tsiotras, G. Multiple perspectives on integrated management systems and corporate sustainability performance. *J. Clean. Prod.* **2017**, *168*, 1297–1311. [CrossRef]
91. Huovila, A.; Bosch, P.; Airaksinen, M. Comparative analysis of standardized indicators for Smart sustainable cities: What indicators and standards to use and when? *Cities* **2019**, *89*, 141–153. [CrossRef]
92. Audretsch, D.B.; Cunningham, J.A.; Kuratko, D.F.; Lehmann, E.E.; Menter, M. Entrepreneurial ecosystems: Economic, technological, and societal impacts. *J. Technol. Transf.* **2019**, *44*, 313–325. [CrossRef]
93. Wilkinson, H.; Hills, D.; Penn, A.; Barbrook-Johnson, P. Building a system-based Theory of Change using Participatory Systems Mapping. *Evaluation* **2021**, *27*, 80–101. [CrossRef]
94. Settembre Blundo, D.; Maramotti Politi, A.L.; Fernández del Hoyo, A.P.; García Muiña, F.E. The Gadamerian hermeneutics for a mesoeconomic analysis of Cultural Heritage. *J. Cult. Herit. Manag. Sustain. Dev.* **2019**, *9*, 300–333. [CrossRef]
95. Bellucci, F.; Pietarinen, A.V. Peirce on the justification of abduction. *Stud. Hist. Philos. Sci. Part A* **2020**, *84*, 12–19. [CrossRef] [PubMed]
96. LIFE Force of The Future. "New Circular Business Concepts for the Predictive and Dynamic Environmental and Social Design of the Economic Activities". LIFE16 ENV/IT/000307. Available online: https://webgate.ec.europa.eu/life/publicWebsite/index.cfm?fuseaction=search.dspPage&n_proj_id=6205 (accessed on 1 September 2021).
97. Pradel, M.; Aissani, L. Environmental impacts of phosphorus recovery from a "product" Life Cycle Assessment perspective: Allocating burdens of wastewater treatment in the production of sludge-based phosphate fertilizers. *Sci. Total Environ.* **2019**, *656*, 55–69. [CrossRef]
98. Martínez-Blanco, J.; Forin, S.; Finkbeiner, M. Challenges of organizational LCA: Lessons learned from road testing the guidance on organizational life cycle assessment. *Int. J. Life Cycle Assess.* **2020**, *25*, 311–331. [CrossRef]
99. Porter, M.E. Competitive Advantage: Creating and sustaining superior performance. *Free Press* **1985**, *167*, 167–206.
100. Koc, T.; Bozdag, E. Measuring the degree of novelty of innovation based on Porter's value chain approach. *Eur. J. Oper. Res.* **2017**, *257*, 559–567. [CrossRef]
101. Yazdi, P.G.; Azizi, A.; Hashemipour, M. An empirical investigation of the relationship between overall equipment efficiency (OEE) and manufacturing sustainability in industry 4.0 with time study approach. *Sustainability* **2018**, *10*, 3031. [CrossRef]
102. Janasekaran, S.; Lim, S.H. Reduction of Non Added Value Activities During Machine Breakdown to Increase Overall Equipment Efficiency: Surface Mounting Technology Production Case Study. In *Lecture Notes in Mechanical Engineering*; Springer: Singapore, 2020; pp. 51–56.
103. Durán, O.; Durán, P.A. Prioritization of physical assets for maintenance and production sustainability. *Sustainability* **2019**, *11*, 4296. [CrossRef]
104. Mazziotta, M.; Pareto, A. Methods for constructing composite indicators: One for all or all for one. *Ital. J. Econ. Demogr. Stat.* **2013**, *67*, 67–80.
105. Paruolo, P.; Saisana, M.; Saltelli, A. Ratings and rankings: Voodoo or science? *J. R. Stat. Soc. Ser. A Stat. Soc.* **2013**, *176*, 609–634. [CrossRef]
106. Naghshineh, B.; Lourenço, F.; Godina, R.; Jacinto, C.; Carvalho, H. A social life cycle assessment framework for additive manufacturing products. *Appl. Sci.* **2020**, *10*, 4459. [CrossRef]
107. Langhans, S.D.; Reichert, P.; Schuwirth, N. The method matters: A guide for indicator aggregation in ecological assessments. *Ecol. Indic.* **2014**, *45*, 494–507. [CrossRef]
108. D'Adamo, I.; Gastaldi, M.; Rosa, P. Recycling of end-of-life vehicles: Assessing trends and performances in Europe. *Technol. Forecast. Soc. Chang.* **2020**, *152*, 119887. [CrossRef]
109. D'adamo, I.; González-Sánchez, R.; Medina-Salgado, M.S.; Settembre-Blundo, D. E-commerce calls for cyber-security and sustainability: How european citizens look for a trusted online environment. *Sustainability* **2021**, *13*, 6752. [CrossRef]