sustainability

Article

A Framework for Sustainable Manufacturing: Integrating Industry 4.0 Technologies with Industry 5.0 Values

Alejandro M. Martín-Gómez , Alejandro Agote-Garrido * and Juan Ramón Lama-Ruiz

Design Engineering Department, Higher Polytechnic School, University of Seville, 41011 Seville, Spain; ammartin@us.es (A.M.M.-G.); jrlama@us.es (J.R.L.-R.)
* Correspondence: aagote@us.es

Abstract: The limitations imposed by resource scarcity and the imperative to mitigate adverse environmental and societal impacts have intensified the urgency of developing more sustainable manufacturing systems. Simultaneously, the rapid development and implementation of new technologies is exacerbating the digital divide among vulnerable workers. Concomitantly, the enabling technologies stemming from Industry 4.0 offer significant potential to enhance the competitiveness of manufacturing systems. However, the impact of these enabling technologies on achieving sustainable manufacturing remains uncertain. This paper embarks on a comprehensive exploration to address this knowledge gap. Initially, it assesses the suitability of each enabling technology within Industry 4.0 across the economic, social, and environmental dimensions of sustainability. Subsequently, the needs of the production process are studied to characterize its sustainable performance. For this, the ASTM E3012-22 standard is introduced. Building upon this foundation, the incorporation of Industry 5.0 is introduced to guide the selection of enabling technologies for sustainability based on its core values, encompassing sustainability, human-centricity, and resilience. The integration of new technologies guided by these values can help bridge the technological divide among vulnerable workers. Finally, a theoretical framework is proposed to enable the design of sustainable manufacturing systems guided by Industry 5.0 values. This framework enables the seamless integration of enabling technologies, machinery, and human expertise throughout the system life cycle.

Keywords: Industry 4.0 technology; Industry 5.0; digital transformation; sustainable manufacturing; smart manufacturing systems

Citation: Martín-Gómez, A.M.; Agote-Garrido, A.; Lama-Ruiz, J.R. A Framework for Sustainable Manufacturing: Integrating Industry 4.0 Technologies with Industry 5.0 Values. *Sustainability* **2024**, *16*, 1364. https://doi.org/10.3390/su16041364

Academic Editors: Maria Palazzo, Alessandra Micozzi and Dominique Lepore

Received: 31 December 2023
Revised: 24 January 2024
Accepted: 5 February 2024
Published: 6 February 2024

1. Introduction

Industry 4.0 represents a significant evolution in the industrial landscape due to the incorporation of information and communication technologies (ICTs) [1]. Big Data and Artificial Intelligence enable operational improvement, elevating business performance to new levels [2,3]. However, the capacity of these technologies to foster a deeper context of sustainability is often underestimated [4]. At a time when many sustainability tipping points are considered surpassed [5], organizations have the responsibility and opportunity to lead the way toward a more equitable and sustainable future. Studies must shift their focus to analyze these technologies not only as drivers of innovation and competitiveness but as instruments for positive global change [6].

Sustainability can be analyzed in three dimensions: the social, environmental, and economic dimensions. The aim of ensuring a framework that balances a company in these three perspectives is called the "triple bottom line" (3BL) [7]. Sustainability has gained increasing consideration in the industrial sector in recent years, emerging among the key strategic objectives of an expanding number of manufacturing companies [8]. This has led researchers like Awan to develop approaches that transform the industrial sector towards a more sustainable purpose [9]. For instance, Circular Economy (CE) is considered a viable approach to improve environmental impact while maintaining economic profitability [10].

CE pays special attention to material optimization and waste minimization, thus developing a more sustainable production process [11].

The practice of evaluating or comparing the sustainability of a production process is sometimes inconsistent. Uniform methods representing processes and equipment, where manufacturers gather necessary data and characterize their systems, are still lacking [12]. To address this situation, ASTM International develops standards to aid in characterizing manufacturing processes [13]. The characterization of systems is carried out through the graphical representation of processes involving multiple unit manufacturing processes (UMPs). ASTM defines, through its guidelines, a generic structure for representing information and linking multiple UMPs. This structure allows the simulation and evaluation of the product (micro), production line (meso), and industrial organization (macro) levels.

Industry 5.0 emerges with a focus on values of social responsibility, environmental consciousness, and resilience [14]. This industrial revolution allows a shift in the current paradigm, centering manufacturing principles on achieving an industrial system respectful of humanity, mindful of the environment, and committed to its continuity over time. Industry 5.0 leverages enabling technologies developed during the fourth industrial revolution while continuing technological development. However, in both scenarios, it prioritizes the respect for the values that characterize it [15]. This consideration sets the path toward mitigating the gap between sustainability and technological development [16].

The incorporation of innovative technologies in industrial activities has emerged as a key element to improve the internal management of companies [17]. These technologies significantly transform production processes, boosting efficiency and competitiveness [18]. However, the move towards Industry 5.0, a paradigm still in its early stages, presents new challenges and opportunities. The literature review developed reflects that there is a gap regarding how Industry 4.0 enabling technologies can be effectively assessed and applied under the core values of Industry 5.0, especially in terms of sustainability. The study developed here makes a significant contribution to the field of industrial sustainability in two main ways. Firstly, it provides a detailed exploration of how emerging technologies from Industry 4.0 can be assessed under the core values of Industry 5.0, with a particular focus on the three dimensions of sustainability. Secondly, it introduces an innovative framework designed to guide the effective incorporation of technologies and values into sustainable manufacturing systems. The study combines a literature review with original research. The literature review gathers the main enabling technologies from Industry 4.0 and establishes the needs and opportunities in the context of sustainability. This theoretical background is essential for developing the proposed methodological framework.

The study has the following aims: (a) providing knowledge that helps bridge the existing gap between the implementation of Industry 4.0 enabling technologies and the values that characterize the Industry 5.0; (b) evaluating the suitability of emerging technologies in relation to the economic, social, and environmental dimensions of sustainability; (c) offering a preliminary theoretical framework for industries and academics on how to select and apply these technologies in a way that aligns with the core values of Industry 5.0.

The manuscript is organized as follows: (1) Introduction. It presents the research problem and contextualizes the study. (2) Background. This section presents the main frameworks that allow the incorporation of technologies into a production process. Additionally, it identifies and characterizes the main enabling technologies and their relationship with sustainability. (3) Production process. Defines the characterization for a production process according to the ASTM E3012-22 standard [19]. (4) Industry 5.0. Defines and identifies the values of the new industrial paradigm. (5) Design framework. Develops the theoretical design framework. (6) Conclusions. Presents the conclusions, implications, and recommendations for future research and industrial applications.

2. Background

2.1. Frameworks for Incorporating Technology into the Production Process

The implementation of technology in manufacturing processes has always been a challenge [20]. However, the development of increasingly complex technologies has exacerbated this situation in the industrial environments of Industry 4.0 [21]. This has been of interest to researchers, and the existing literature already includes several frameworks proposed to facilitate integration [22]. Butt proposes a conceptual framework that supports digital transformation in manufacturing through a business process management (BPM) approach. However, this framework is solely based on factors that minimize the risk of failure [23]. Other authors like Yadav developed a framework more oriented towards the characteristics of this manuscript. This author presents a framework for achieving sustainability in the industrial organization using Industry 4.0 enabling technologies [24]. The study identifies the facilitators and uses the robust best–worst method (RBWM) to identify the influence of each indicator [25]. Although it is interesting how it presents a case of application of the proposed framework, it does not consider the social aspect of sustainability, obtaining only economic and environmental results.

The framework proposed in this manuscript aims to address the limitations of the identified frameworks and provide a characterization of sustainability in its three perspectives. Furthermore, the proposal not only focuses on the technical integration of advanced technologies in line with sustainability but also considers their interaction in accordance with the values of Industry 5.0. The aim is to present a more holistic and balanced approach. It seeks to continue improving efficiency and productivity but, above all, to also ensure sustainable and responsible practices in manufacturing that align with human and environmental values.

2.2. Enabling Technologies of Industry 4.0

Industry 4.0 promotes the development of a wide variety of ICTs. These enable the advancement of production systems, making them more digital and automated [1]. This leads to improvements in product quality and reduces cycle time, ultimately reflecting better overall company performance [4]. Furthermore, Industry 4.0 ICTs promote the creation of synergistic work environments between the physical and the real world. Real-time availability of information through Cyber-Physical Systems (CPS) allows higher levels of automation and achieves better performance [26]. Industry 4.0 technologies can take various forms, such as the internet of things, cloud computing, augmented reality, big data analytics, or additive manufacturing. Table 1 presents the main enabling technologies of Industry 4.0 with a brief description of each, derived from the literature analysis. The technologies are classified into two major groups: physical and non-physical technologies [27].

Table 1. Classification of the main enabling technologies of Industry 4.0.

Physical Technologies		
Internet of Things (IoT)	Connection and communication between devices and systems in real-time.	[28]
Robotics and Automation	Use of robots and automated systems for production tasks.	[29]
Augmented Reality and Virtual Reality	Immersive experiences and overlay of digital information.	[30]
3D Printing or Additive Manufacturing	Creation of three-dimensional objects from a digital design.	[31]
Smart Sensors	Devices that collect and process information from the environment and automatically adjust operations in response.	[32]
Autonomous Transport Systems	Vehicles and drones that move without direct human intervention.	[33]
Nanotechnology	Manipulation of matter at an atomic or molecular scale.	[34]

Table 1. *Cont.*

Non-Physical Technologies		
Big Data and Data Analysis	Collection, storage, and analysis of large amounts of data.	[35]
Cloud Computing	Storage and access to data and programs over the internet.	[36]
Simulation	Virtual models to simulate physical systems.	[37]
Cybersecurity	Protection of systems, networks, and programs against digital attacks.	[38]
System Integration	Connection and collaboration between different systems and technologies.	[39]
Artificial Intelligence	Virtual system capable of performing tasks that require human intelligence.	[40]
Machine Learning	Discipline that, using algorithms, allows computers to identify patterns.	[41]
Blockchain	Distributed ledger technology that facilitates secure transactions on a network.	[42]

The implementation of the IoT provides companies with a quick response to customer needs, optimizing deliveries [43]. Cloud manufacturing and big data enable a reduction in operational costs by proactively identifying issues in machines [44]. This is made possible by combining these technologies with the use of smart sensors. Additive manufacturing provides competitive advantages in post-sales processes, creating new revenue streams [45]. Additionally, technologies such as virtual reality or augmented reality offer training and information to employees, resulting in faster and more accurate task execution [46]. Digital twin technology also accelerates the learning capability of the worker and allows cost savings by testing initial products in a virtual environment [47].

The development and implementation of these technologies bring forth different conflicts to be addressed by leading researchers in the field. For example, machine connectivity poses reliability issues. There is a study on how these can be resolved by enhancing efficiency standards [48]. Security issues of ICTs are also urgently addressed to ensure more reliable product lines for customers [49]. However, the gap addressed by this study is a discussion of the benefits of these technologies concerning sustainable manufacturing. Industry 4.0 has enormous potential to achieve a sustainable production process that enhances procedures, reduces delivery times, and improves corporate efficiency. However, this industrial paradigm, due to its focus on technological development, continues to face various obstacles and threats regarding sustainability [50]. This justifies the interest in the study conducted in the present manuscript.

2.3. The Sustainable Nature of Enabling Technologies in Industry 4.0

Sustainable manufacturing is understood as an inclusive initiative necessary to promote the economic, social, and environmental dimensions of sustainability [51]. This is a dynamic concept, as its scope and implications evolve over time [52]. Industry 4.0 promotes some aspects of environmental sustainability, especially at a factory level [53]. ICTs, for example, can contribute to reducing energy consumption or emissions, thanks to the use of technologies such as the IoT or additive manufacturing [54]. However, the development of other technologies such as Artificial Intelligence or robotics has been detrimental to various socio-environmental aspects, particularly at a macroscopic level (industrial organization) [55].

Sustainability has gained increasing consideration from manufacturing companies. Having a sustainable organization for the environment, society, and the economy is currently considered attractive [56]. However, most companies still grapple with the negative effects they generate on society and the environment. The problem lies in the balance of costs and benefits [57]. Companies tend to opt for economically driven production, rather than producing more expensive products with a less negative impact on sustainability.

Despite this, Industry 4.0 brings a positive increase in the sustainability of organizations due to the development of ICTs [58].

Social sustainability addresses the impact of industrial activity on people directly or indirectly involved with it. It involves ensuring safe and fair working conditions [59]. This approach aims to make industrial practices and their associated technology ethically responsible, generating a positive impact on society [60]. Social sustainability promotes equity, diversity, and respect for human rights to achieve an environment of growth and innovation [7]. Environmental sustainability addresses the impact of industrial activity on the environment. It involves policies such as efficient resource management, waste reduction, minimization of the carbon footprint, and pollution prevention [61]. Additionally, it considers aspects such as atmospheric emissions and the efficient use of water [62]. The aim of this approach is to preserve, or if possible, restore and enhance the planet. Economic sustainability addresses the ability to obtain economic benefits derived from industrial activity over time without compromising social or environmental sustainability [63]. This approach considers operational efficiency and adaptability to market changes for value creation [64]. The indicator of economic performance is essential for a company to operate with a long-term perspective [65].

The characterization of the main enabling technologies of Industry 4.0 considered in this study, according to the three dimensions of sustainability, is presented in Table 2. This table, gathered from the analyzed literature, shows how the main technologies of Industry 4.0 contribute to sustainability in the social (blue), environmental (green), and economic (red) dimensions [18,66–68]. The characterization is applied to the technologies listed in Table 1 and maintains their classification into physical and non-physical technologies.

Table 2. Characterization of Industry 4.0 technologies in terms of sustainability.

Physical Technologies	
Internet of Things (IoT)	(So) Improves workplace safety by monitoring conditions in real time. (Ev) Enables real-time monitoring of resource usage, aiding in efficient management. (Ec) Optimizes production and reduces costs by providing accurate data for decision making.
Robotics and Automation	(So) Can replace hazardous works but also poses challenges in terms of employment. (Ev) Improves process efficiency, reducing waste and consuming fewer resources. (Ec) Increases productivity and reduces operating costs.
Augmented Reality and Virtual Reality	(So) Empowers workers through virtual training and assistance. (Ev) Reduces the need for physical prototypes and travel, saving resources. (Ec) Accelerates product design and development, reducing time to market.
3D Printing or Additive Manufacturing	(So) Enables product customization and adaptability to specific needs. (Ev) Minimizes waste by using only the necessary material. (Ec) Reduces costs associated with mass production and enables on-demand manufacturing.
Smart Sensors	(So) Enhance safety by detecting abnormal conditions in the work environment. (Ev) Monitor resource consumption and emissions, facilitating environmental management. (Ec) Optimize operation by providing precise information for maintenance and production.
Autonomous Transport Systems	(So) Reduce accidents by automating transportation tasks. (Ev) Potential to optimize routes and reduce emissions if combined with clean energy. (Ec) Improves logistical efficiency and reduces costs associated with human errors.
Nanotechnology	(So) Enables developments in medicine and materials to improve the quality of life. (Ev) Allows the creation of more efficient and sustainable materials. (Ec) Enables the opening of new markets and applications for innovative products.

Table 2. *Cont.*

Non-Physical Technologies	
Big Data and Data Analysis	(So) Enables data-driven decision making to enhance the quality of life and services. (Ev) Assists in monitoring and managing environmental impacts. (Ec) Optimizes operations and business strategies, increasing profitability.
Cloud Computing	(So) Enables collaboration and access to information from anywhere. (Ev) Reduces the need for physical infrastructure and optimizes the use of resources. (Ec) Lowers costs associated with hardware and IT maintenance.
Simulation	(So) Enables training and education in secure environments. (Ev) Reduces the need for physical prototypes and tests that consume resources. (Ec) Accelerates design and development, reducing costs associated with testing and errors.
Cybersecurity	(So) Protects the privacy and data of individuals. (Ev) Ensures the integrity of systems monitoring and managing environmental impacts. (Ec) Safeguards business assets and prevents financial losses from attacks.
System Integration	(So) Enables interaction between different teams and departments, improving job satisfaction. (Ev) Allows more efficient use of resources by enhancing coordination between processes. (Ec) The effective integration of systems can lead to higher productivity.
Artificial Intelligence	(So) Enhances the ability to make decisions that impact social aspects. (Ev) Ensures smarter resource allocation through advanced data analysis. (Ec) Optimizes business models through supply chain optimization.
Machine Learning	(So) Provides human-centric services. (Ev) Reduces waste through predictive analytics. (Ec) Improves efficiency through better pattern prediction.
Blockchain	(So) Increases transparency and reliability in transactions and agreements. (Ev) Enables tracking and verification of sustainable products. (Ec) Reduces costs associated with intermediaries and fraud.

(So) Social Sustainability; (Ev) Environmental Sustainability; (Ec) Economic Sustainability.

It is justified in Table 2 how emerging technologies from Industry 4.0 possess characteristics that enable them to promote industrial sustainability in the social, environmental, and economic dimensions. The Internet of Things (IoT) offers monitoring of working conditions that significantly improves workplace safety [69]. Robotics, although posing challenges in terms of employment, reduce operational costs and resource waste [70]. Similarly, additive manufacturing allows for more personalized production with less material waste. This provides clear environmental and economic benefits [71]. Furthermore, technologies such as virtual reality save financial resources and reduce the carbon footprint by avoiding in-person visits and travel [72]. The technologies described not only strengthen the capacity of companies to be competitive but also align them with the growing demands for responsibility and sustainability. This sets the stage for the transition to the values and practices of Industry 5.0 [73].

3. Production Process

The production process is generally defined as an industrial activity that uses energy to transform raw materials into a product [74]. In each industrial activity, there can be multiple ways of operation, various sources of energy, types of materials, and a required final quality of the resulting product. Therefore, the definition of a common information model facilitates the evaluation of each alternative across different domains [75]. The procedure of describing and categorizing the performance of a manufacturing process is called process characterization [76]. It identifies key aspects such as the inputs and outputs of the process, product information, and the transformation of resources [77].

Characterization of the Production Process

The data obtained from a characterization can be used in different types of evaluations. However, the scope of this study focuses the obtained information on a sustainability assessment [78]. Sustainability should be understood as a multicriteria decision-making problem [79]. For a manufacturing process to be integrated into a multicriteria evaluation, a prior virtual evaluation of different manufacturing options is necessary [80]. To facilitate this type of evaluation, a series of "plugs" must be provided. These are understood as the most basic components from which to create virtual representations of manufacturing systems. Connecting these plugs represents the flow of materials, information, and energy within the systems [12]. The ASTM E3012-22 standard defines the characteristics that these plugs must have and proposes virtual representations of UMPs.

Figure 1 presents the virtual representation of a generic manufacturing process and the diagram of a generic UMP. This unit is used to describe the transformation of energy, material, or information from inputs to outputs. Material transformations encompass changes in mass, structure, or phase, for example. Energy transformations can be thermal, chemical, or mechanical, among others. Information transformations consider production metrics such as yield. Any of these three transformations uses the information contained in the elements of Product and Process Information and Resources.

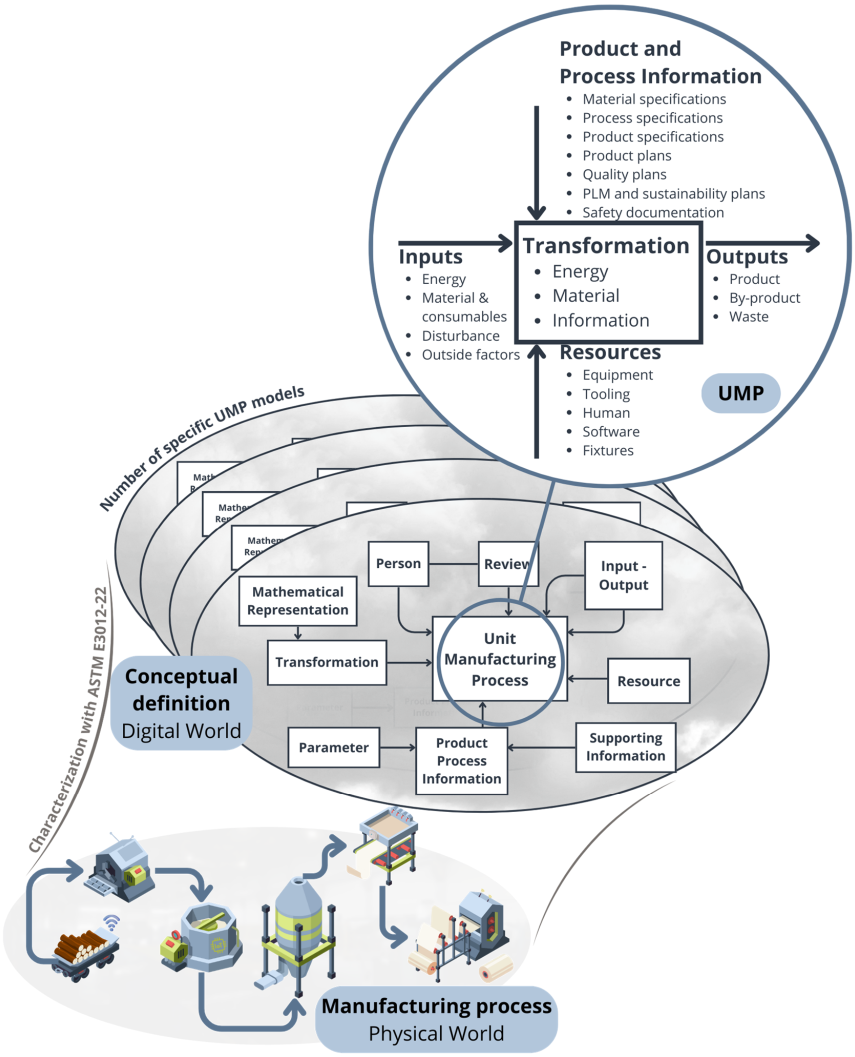

Figure 1. Characterization of the production process according to ASTM E3012-22 standard.

The ASTM standard guides the characterization of the production process to determine the sustainable performance of each of its stages. This is crucial for controlling and mitigating the social, environmental, and economic impact throughout its entire lifecycle [81]. However, breaking down a process into its different stages enables addressing other topics of interest, as is the case in this study with the use of technology. Some studies already present the classification of ICTs in the different stages of a production process within the context of Industry 4.0 [82]. The aim is to determine how each technology can support or limit each stage of the production process.

4. Industry 5.0

Researchers rely on the aforementioned controversies triggered by the Industry 4.0 model to define the upcoming industrial paradigm. The European Commission has expressed that while Industry 4.0 has not yet reached its peak maturity, this framework is no longer suitable for an industrial network where sustainability is an indispensable aim [83]. The scientific community is already offering preliminary ideas about the new industrial paradigm and its sustainable approach. Dwivedi highlights synergies between Industry 5.0 and the circular supply chain [84]. Other authors, such as Ivanov, emphasize potential values of sustainability in Industry 5.0 [14]. This demonstrates the considerable efforts to expand the concept of Industry 5.0 and gain a deeper understanding of it.

The study of sustainability in the context of Industry 4.0 is relatively well consolidated [85]. However, it is not advisable to extend these previous findings to the context of Industry 5.0 to address this knowledge gap. This is because the focus of both industrial contexts is entirely different. Industry 4.0 is an industrial paradigm based on technological drive and productivity [86]. In contrast, Industry 5.0 is grounded in values centered on humanity, the environment, and process continuity [87]. Figure 2 illustrates how these three approaches of Industry 5.0 are closely related to the three perspectives of sustainability. The human-centered approach strengthens the social perspective of sustainability. It aims to ensure the well-being of all human beings involved in the industrial context. In it, values such as autonomy, privacy, or security are considered [88]. The sustainable approach focuses on the continuity of the system. It encompasses the three perspectives of sustainability by itself. It considers values such as diversity or equity [89]. The resilient approach allows the system to become robust. It focuses on the industrial system positively adapting to changes and facing adversities. It considers values such as adaptability or leadership [90].

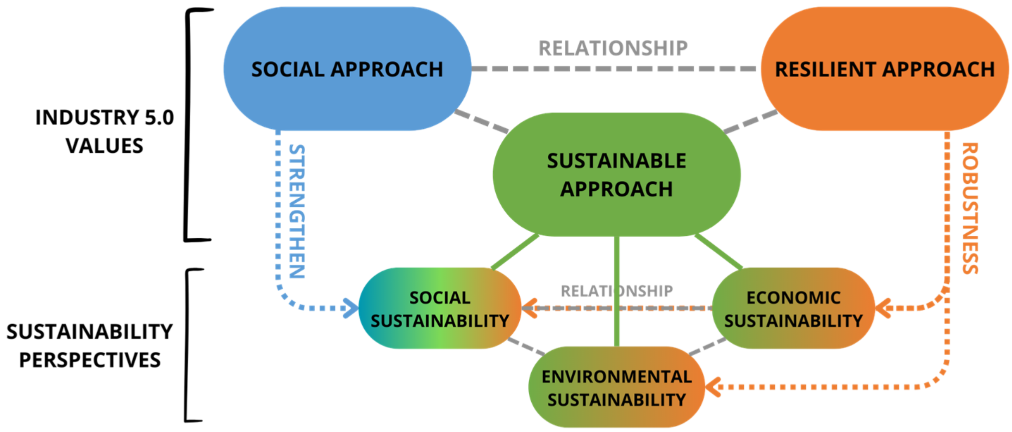

Figure 2. Sustainability from the approach of Industry 5.0.

The current literature on the subject compiles 12 functions through which Industry 5.0 can contribute to sustainable manufacturing [91]. These functions allow personifying the abstract concepts that are the values to assess their compliance. Manufacturing circularity (MCR) enables reducing environmental impact by optimizing systems [92]. Manufacturing strategic adaptability (MAP) empowers manufacturers to adjust their operations to changes in their environment efficiently [93]. Manufacturing productivity (MPD) addresses the complexity of supply networks and production models to decrease risks that harm productivity [94]. Renewable integration (RIT) involves the use of renewable energy sources in manufacturing processes to achieve cleaner production [95]. Sustainable skill development (SKD) prioritizes the human approach by engaging stakeholders, driving system improvement [96]. Manufacturing resilience (MNR) enables a quick response to disruptions and effective adaptation to changing circumstances [97].

Manufacturing responsiveness (MRS) enables total visibility into the entire product lifecycle, minimizing production costs [98]. Sustainable technology governance (STG) considers sustainability values in the design, implementation, and operation of new technology [99]. Sustainable business model innovation (SBI) promotes collaboration among all stakeholders in sustainable innovation, with a focus on manufacturers and technology providers [100]. Work environment smartification (WES) involves adapting technologies to the needs of workers without compromising their autonomy and psychology [101]. Sustainable employment (SEP) encompasses strategies to help individuals secure stable and satisfying employment [102]. Value network integration (VNI) establishes the premise that information technologies and the operations of all stakeholders should be able to seamlessly exchange information when necessary without issues [53]

5. Design Framework

The proposed framework for the integration of Industry 4.0 technologies and their environmental aspects into the stages of a production process based on the values of Industry 5.0 is presented in Figure 3. The relationship between technologies, stages, and sustainability is represented in the form of a three-dimensional matrix. At the top, the relationships between enabling technologies and the stages that make up the production process are reflected to determine in which stages they can be employed a priori. On the left side of the matrix, technologies are related to sustainability in its three perspectives. To do this, technologies must first be identified and characterized and sustainable characteristics selected. This can be performed using tools such as SWOT analysis or benchmarking. On the right side of the matrix, the stages of the production process are related to the sustainable requirements they need to meet. To do this, a production process must first be defined, with its different stages analyzed, and then characterized in terms of sustainability. For this, the ASTM E3012-22 standard is used.

All relationships between technology, stages, and sustainability reflect gradual results within a range from 0 to 1. These values define the degree of satisfaction for each relationship. When it is determined that several technologies can be used in a stage and have a set of sustainable characteristics that match the requirements of that stage, it is time to integrate them from the perspective of Industry 5.0 values. To do this, the first step is to select which technology best satisfies the values. Tools that enable this analysis include the QFD matrix, AHP, or the BSC. Once the technology is selected, the functions identified in the study are used for its integration. Finally, this process must be continuously evaluated and feedbacked to ensure that if new values emerge they are considered and that no conflicting values are encountered.

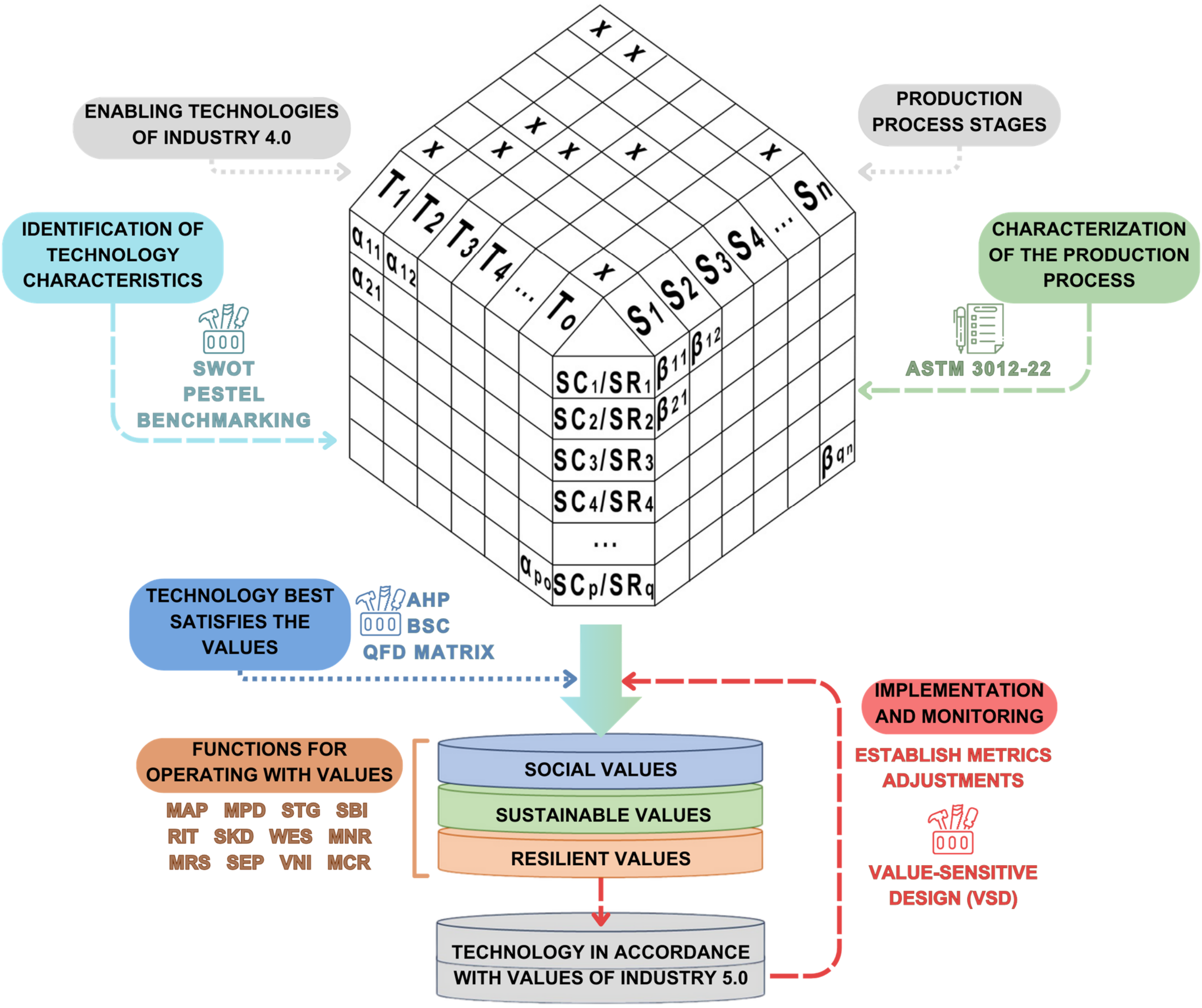

Figure 3. A framework for sustainable manufacturing: integrating Industry 4.0 technologies with Industry 5.0 values.

5.1. Identification of Stages and Technologies

The first step in applying the proposed model is to break down the industrial process (P). The process to be evaluated must be analyzed by dividing it into clearly defined stages (S). Among the most common stages of any production process, one can include the acquisition of raw materials, assembly, manufacturing, or quality control, for example [103].

$$[P] = [S_1, S_2, \ldots, S_m, \ldots, S_n] \tag{1}$$

where:

- P: Presents the entire process.
- S: Stage of the process (S_1, S_2, . . ., S_m, . . ., S_n), with m being a natural number ranging from [1, n].

Each of the identified stages can make use of one or several technologies. These technologies, depending on their characteristics, can either benefit or limit that stage of the process [20]. The selection of technologies considers the various enabling technologies of Industry 4.0. The selection of technologies can be carried out through a SWOT analysis, expert consultation, or benchmarking, among other methods [104].

5.2. Evaluation of Sustainability Characteristics

Technologies possess various characteristics that make them unique compared to others. These characteristics define their nature in technical, social, environmental, legal, or operational aspects, among others [105]. However, the evaluation and selection of each technology in this study focus on its sustainability characteristics. Table 3 represents the classification of technologies by stages and their contribution, based on their characteristics, to the three sustainability perspectives. Among the sustainability-related technology characteristics, one can observe the development of skills in the workforce, the ability to use renewable energy sources, or the capacity to adapt to changes in the process [106].

Table 3. Matrix of relationship between Industry 4.0 technologies and sustainability, classified by stages [own study].

S	T	SC_{So}	SC_{Ev}	SC_{Ec}
S_1	T_1 T_m	$\alpha_{So,1,1}$ $\alpha_{So,1,m}$	$\alpha_{Ev,1,1}$ $\alpha_{Ev,1,m}$	$\alpha_{Ec,1,1}$ $\alpha_{Ec,1,m}$
S_2	T_2	$\alpha_{So,2,2}$	$\alpha_{Ev,2,2}$	$\alpha_{Ec,2,2}$
S_3	T_2 T_3	$\alpha_{So,3,2}$ $\alpha_{So,3,3}$	$\alpha_{Ev,3,2}$ $\alpha_{Ev,3,3}$	$\alpha_{Ec,3,2}$ $\alpha_{Ec,3,3}$
...	...	...	...	...
S_n	T_1 T_2 T_o	$\alpha_{So,n,1}$ $\alpha_{So,n,2}$ $\alpha_{So,n,o}$	$\alpha_{Ev,n,1}$ $\alpha_{Ev,n,2}$ $\alpha_{Ev,n,o}$	$\alpha_{Ec,n,1}$ $\alpha_{Ec,n,2}$ $\alpha_{Ec,n,o}$

where:

- S: Stage of the process (S_1, S_2, . . ., S_m, . . ., S_n), with m being a natural number ranging from [1, n].
- T: Technology used in that stage (T_1, T_2, ..., T_m, ..., T_o), with m being a natural number ranging from [1, o].
- SC_{So}: Social sustainability characteristics.
- SC_{Ev}: Environmental sustainability characteristics.
- SC_{Ec}: Economic sustainability characteristics.
- $\alpha_{So,n,o}$: Contribution of technology T_m in stage S_m in terms of social sustainability. This is a real number in the range of [0, 1].
- $\alpha_{Ev,n,o}$: Contribution of technology T_m in stage S_m in terms of environmental sustainability. This is a real number in the range of [0, 1].
- $\alpha_{Ec,n,o}$: Contribution of technology T_m in stage S_m in terms of economical sustainability. This is a real number in the range of [0, 1].

The results obtained outline a series of technologies that: (1) due to their general characteristics can be used in a specific stage of a production process, and (2) within that stage, they either contribute or do not contribute to certain characteristics that can favor sustainability in the process. However, it is necessary to define the sustainability needs of the production process. This characterization is carried out following the ASTM E3012-22 standard. The guidelines of this standard allow for the collection of relevant data to identify the process according to the sustainability criteria established by the standard. The analysis is carried out following criteria such as resource efficiency, waste management, and emission reduction, among others [107]. The sustainability requirements of each stage of the process are reflected in matrix form in Table 4.

Table 4. Matrix of relationship between stages of the production process and sustainable manufacturing requirements [own study].

	SR_{So}	SR_{Ev}	SR_{Ec}
S_1	$\beta_{So,1}$	$\beta_{Ev,1}$	$\beta_{Ec,1}$
S_2	$\beta_{So,2}$	$\beta_{Ev,2}$	$\beta_{Ec,3}$
S_3	$\beta_{So,3}$	$\beta_{Ev,3}$	$\beta_{Ec,3}$
…	…	…	…
S_n	$\beta_{So,n}$	$\beta_{Ev,n}$	$\beta_{Ec,n}$

where

- S: Stage of the process ($S_1, S_2, \ldots, S_m, \ldots, S_n$), with m being a natural number ranging from [1, n].
- SR_{So}: Social sustainability requirements.
- SR_{Ev}: Environmental sustainability requirements.
- SR_{Ec}: Economic sustainability requirements.
- $\beta_{So,n}$: Indicates if the stage has specific social sustainability requirements. This is a real number in the range of [0, 1].
- $\beta_{Ev,n}$: Indicates if the stage has specific environmental sustainability requirements. This is a real number in the range of [0, 1].
- $\beta_{Ec,n}$: Indicates if the stage has specific economic sustainability requirements. This is a real number in the range of [0, 1].

5.3. Sustainability-Based Selection

The sustainability characteristics possessed by the technologies to be used in each stage of the process (Table 3) are the ones that will satisfy the sustainability requirements of each stage (Table 4). For the mathematical representation of the relationship between the process stages, the technologies, and how the sustainability characteristics of these technologies satisfy the sustainable requirements of the process, the function of Equation (2) is defined.

$$C(S_i, T_j) = \left(c_{So}(S_i, T_j), c_{Ev}(S_i, T_j), c_{Ec}(S_i, T_j)\right) \quad (2)$$

where

- S_i: Stage of the process ($S_1, S_2, \ldots, S_m, \ldots, S_n$), with m being a natural number ranging from [1, n].
- T_j: Represents a technology of Industry 4.0 with *j* being a natural number ranging from [1, o].
- $C(S_i,T_j)$: Represents the degree of compliance with the sustainability requirements of stage S_i by technology T_j in terms of social, environmental, and economic sustainability.
- $c_{So}(S_i,T_j)$, $c_{Ev}(S_i,T_j)$, $c_{Ec}(S_i,T_j)$: Indicate the degree of compliance in each of the sustainability aspects. Each of these can be defined following what is represented in Equations (3)–(5).

$$c_{So}(S_i, T_j) = \min\left(1, \frac{\alpha_{So,i,j}}{\beta_{So,i,j}}\right) \quad (3)$$

$$c_{Ev}(S_i, T_j) = \min\left(1, \frac{\alpha_{Ev,i,j}}{\beta_{Ev,i,j}}\right) \quad (4)$$

$$c_{Ec}(S_i, T_j) = \min\left(1, \frac{\alpha_{Ec,i,j}}{\beta_{Ec,i,j}}\right) \quad (5)$$

The min function ensures that the value does not exceed 1. The defined mathematical representation provides the degree to which the characteristics of technologies meet the requirements of a stage in the process. In the case of indicating the value 1, the technology fully complies with or exceeds the sustainability requirement of a stage. However, a value less than 1 indicates a proportional degree of compliance.

5.4. Integration with the Values of Industry 5.0

The final selection of technologies is guided by the values of Industry 5.0. These values should be the foundation for decision making regarding which technology to use when multiple options are available. The first step is to identify values, which can either be inherent to the technology to be used or can derive from the strategic management of the company [108]. Values are categorized into three main approaches: human-centric values, sustainability values, and resilience values. Additionally, values hold strategic importance for the organization, so they should be weighted to align with the mission and vision of the company [109]. Decision making can be facilitated using tools such as the Quality Function Deployment (QFD) matrix, Analytic Hierarchy Process (AHP), or the Balanced Scorecard (BSC).

The values represent abstract theoretical concepts. These need to be personified through contextual designations that serve as a transition point to work with them [110]. Therefore, in the proposed model, the 12 functions compiled from the literature analysis are used. These functions allow for the analysis of the degree of compliance of the sustainable aspect of technologies in accordance with the values of Industry 5.0. The theoretical representation of this process can be expressed through the D function.

$$D\left(S_i, T_j\right) = \left(d_{Hv}\left(S_i, T_j\right), d_{Sv}\left(S_i, T_j\right), d_{Rv}\left(S_i, T_j\right)\right) \quad (6)$$

where

- S_i: Stage of the process (S_1, S_2, . . ., S_m, . . ., S_n), with m being a natural number ranging from [1, n].
- T_j: Represents a technology of Industry 4.0 with *j* being a natural number ranging from [1, o].
- $d_{Hv}(S_i,T_j)$, $d_{Sv}(S_i,T_j)$, $d_{Rv}(S_i,T_j)$: Functions that evaluate technology against the human, sustainable, and resilient values of Industry 5.0.

The definition of the functions $d_{Hv}(S_i,T_j)$, $d_{Sv}(S_i,T_j)$, $d_{Rv}(S_i,T_j)$ in the D function requires associating each focus with the 12 functions identified in the literature. The evaluation based on human values ($d_{Hv}(S_i,T_j)$) can consider, for example, the functions SKD, WES, and SEP. Sustainability evaluation ($d_{Sv}(S_i,T_j)$), may include MCR, RIT, and STG. Resilience evaluation ($d_{Rv}(S_i,T_j)$), can include MAP, MNR, and MRS. Each of these functions contributes with an assigned score. This score can be based on empirical data, subject matter experts, or case studies. The D function combines these evaluations to provide a comprehensive alignment of technology with the values of Industry 5.0.

5.5. Implementation and Monitoring

The last step of the proposed framework involves monitoring the technology that has been ultimately selected after its implementation in the production process. It is necessary to establish metrics and KPIs to monitor the performance of the selected technologies in terms of the values of Industry 5.0. This control allows for adjustments to be made as needed. It is important to establish indicators that continuously evaluate the degree of compliance of the technologies to meet any new values that may arise and to detect if there are any conflicting ones. For this purpose, there are design frameworks such as Value-Sensitive Design (VSD). Through its empirical assessments, VSD ensures that various stakeholders are involved in the process [111].

6. Conclusions

The current study effectively meets the proposed objectives: (a) Knowledge has been provided that contributes to bridging the gap between the implementation of Industry 4.0 technologies and the values of Industry 5.0. The literature shows that enabling technologies, in addition to driving innovation and competitiveness in organizations, have a sustainable character that aligns with the aims of Industry 5.0. (b) Enabling technologies have been evaluated with respect to the social, economic, and environmental dimensions of sustainability. The analysis suggests an effective alignment of the technologies with a comprehensive sustainability approach. The characterization of the sustainability of the technologies allows for their selection and application in a socially responsible, environmentally viable, and economically beneficial manner. (c) A preliminary framework has been presented for the selection and application of enabling technologies, aligned with the values of Industry 5.0. In developing this framework, the lack of uniform methods for evaluating the sustainability of manufacturing processes has been noted. However, it introduces the ASTM E3012-22 standard as a guide for the sustainable characterization of industrial processes. This standard, along with the identification of the sustainable characteristics of technology and the consideration of the values of Industry 5.0, allows for the definition of a theoretical framework for designing sustainable manufacturing processes in the new industrial context. The proposed framework provides an initial roadmap for the design processes of the industry of the future.

The developed manuscript addresses the current gap between technological advancements and sustainable manufacturing practices. It also paves the way for further research in pursuit of a more responsible, secure, and resilient industrial future. Despite the progress that this study may represent, its main limitation is due to the nascent state of Industry 5.0. The analysis developed is based on the data and literature available to date. However, the rapid advancement of emerging technologies and the consolidation of the Industry 5.0 concept could require adjustments or updates to the study in the future. In terms of future directions for research, it is recommended to conduct empirical studies to validate and refine the proposed theoretical framework. This could involve case studies in real industrial contexts. Additionally, future research can explore the use of simulation software to model processes that help predict the impact of technologies on the studied approaches.

Author Contributions: Conceptualization, A.M.M.-G. and A.A.-G.; methodology, A.A.-G. and A.M.M.-G.; validation, A.M.M.-G. and J.R.L.-R.; investigation, A.A.-G. and A.M.M.-G.; writing—original draft preparation, A.A.-G.; writing—review and editing, A.A.-G. and A.M.M.-G.; supervision, A.M.M.-G. and J.R.L.-R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

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

References

1. Javaid, M.; Haleem, A.; Singh, R.P.; Suman, R.; Gonzalez, E.S. Understanding the adoption of Industry 4.0 technologies in improving environmental sustainability. *Sustain. Oper. Comput.* **2022**, *3*, 203–217. [CrossRef]
2. Khan, S.A.R.; Tabish, M.; Zhang, Y. Embracement of industry 4.0 and sustainable supply chain practices under the shadow of practice-based view theory: Ensuring environmental sustainability in corporate sector. *J. Clean. Prod.* **2023**, *398*, 136609. [CrossRef]
3. Toth-Peter, A.; de Oliveira, R.T.; Mathews, S.; Barner, L.; Figueira, S. Industry 4.0 as an enabler in transitioning to circular business models: A systematic literature review. *J. Clean. Prod.* **2023**, *393*, 136284. [CrossRef]
4. Costa, F.; Frecassetti, S.; Rossini, M.; Portioli-Staudacher, A. Industry 4.0 digital technologies enhancing sustainability: Applications and barriers from the agricultural industry in an emerging economy. *J. Clean. Prod.* **2023**, *408*, 137208. [CrossRef]
5. Heredia, J.; McIntyre, J.R.; Rubiños, C.; Santibañez, E.; Flores, A. A configuration approach to explain corporate environmental responsibility behavior of the emerging economies firms at industry 4.0. *J. Clean. Prod.* **2023**, *395*, 136383. [CrossRef]
6. Amis, J.M.; Munir, K.A.; Lawrence, T.B.; Hirsch, P.; McGahan, A. Inequality, Institutions and Organizations. *Organ. Stud.* **2018**, *39*, 1131–1152. [CrossRef]
7. Elkington, J. Partnerships from cannibals with forks: The triple bottom line of 21st-century business. *Environ. Qual. Manag.* **1998**, *8*, 37–51. [CrossRef]
8. Ghaithan, A.M.; Alshammakhi, Y.; Mohammed, A.; Mazher, K.M. Integrated Impact of Circular Economy, Industry 4.0, and Lean Manufacturing on Sustainability Performance of Manufacturing Firms. *Int. J. Environ. Res. Public Health* **2023**, *20*, 5119. [CrossRef]
9. Awan, U.; Sroufe, R.; Shahbaz, M. Industry 4.0 and circular economy: A literature review and recommendations for future research. *Bus. Strateg. Environ.* **2021**, *30*, 2038–2060. [CrossRef]

10. Gusmerotti, N.M.; Testa, F.; Corsini, F.; Pretner, G.; Iraldo, F. Drivers and approaches to the circular economy in manufacturing firms. *J. Clean. Prod.* **2019**, *230*, 314–327. [CrossRef]
11. Cholewa, M.; Minh, L.H.B. PLM Solutions in the Process of Supporting the Implementation and Maintenance of the Circular Economy Concept in Manufacturing Companies. *Sustainability* **2021**, *13*, 10589. [CrossRef]
12. Mani, M.; Larborn, J.; Johansson, B.; Lyons, K.W.; Morris, K.C. Standard representations for sustainability characterization of industrial processes. *J. Manuf. Sci. Eng.* **2016**, *138*, 101008. [CrossRef]
13. Rebouillat, L.; Barletta, I.; Johansson, B.; Mani, M.; Bernstein, W.Z.; Morris, K.; Lyons, K.W. Understanding Sustainability Data through Unit Manufacturing Process Representations: A Case Study on Stone Production. *Procedia CIRP* **2016**, *57*, 686–691. [CrossRef]
14. Ivanov, D. The Industry 5.0 framework: Viability-based integration of the resilience, sustainability, and human-centricity perspectives. *Int. J. Prod. Res.* **2023**, *61*, 1683–1695. [CrossRef]
15. Agote-Garrido, A.; Martín-Gómez, A.M.; Lama-Ruiz, J.R. Manufacturing System Design in Industry 5.0: Incorporating Sociotechnical Systems and Social Metabolism for Human-Centered, Sustainable, and Resilient Production. *Systems* **2023**, *11*, 537. [CrossRef]
16. Akande, A.; Cabral, P.; Casteleyn, S. Evaluación de la brecha entre tecnología y sostenibilidad ambiental de las ciudades europeas. *Inf. Syst. Front.* **2019**, *21*, 581–604. [CrossRef]
17. Bernardo, E.; Sousa, N.; Kastenholz, E. Souvenirs in Tourism Studies: A Bibliometric Retrospective and Future Research Agenda. *Tour. Hosp. Manag.* **2023**, *29*, 249–264. [CrossRef]
18. Jamwal, A.; Agrawal, R.; Sharma, M.; Giallanza, A. Industry 4.0 Technologies for Manufacturing Sustainability: A Systematic Review and Future Research Directions. *Appl. Sci.* **2021**, *11*, 5725. [CrossRef]
19. *ASTM E3012-22*; Standard Guide for Characterizing Environmental Aspects of Manufacturing Processes. ASTM International: West Conshohocken, PA, USA, 2022.
20. Moktadir, A.; Ali, S.M.; Kusi-Sarpong, S.; Shaikh, A.A. Assessing challenges for implementing Industry 4.0: Implications for process safety and environmental protection. *Process. Saf. Environ. Prot.* **2018**, *117*, 730–741. [CrossRef]
21. Xu, M.; David, J.M.; Kim, S.H. The Fourth Industrial Revolution: Opportunities and Challenges. *Int. J. Financial Res.* **2018**, *9*, 90. [CrossRef]
22. Cassoli, B.B.; Jourdan, N.; Nguyen, P.H.; Sen, S.; Garcia-Ceja, E.; Metternich, J. Frameworks for data-driven quality management in cyber-physical systems for manufacturing: A systematic review. *Procedia CIRP* **2022**, *112*, 567–572. [CrossRef]
23. Butt, J. A Conceptual Framework to Support Digital Transformation in Manufacturing Using an Integrated Business Process Management Approach. *Designs* **2020**, *4*, 17. [CrossRef]
24. Yadav, G.; Kumar, A.; Luthra, S.; Garza-Reyes, J.A.; Kumar, V.; Batista, L. A framework to achieve sustainability in manufacturing organisations of developing economies using industry 4.0 technologies' enablers. *Comput. Ind.* **2020**, *122*, 103280. [CrossRef]
25. Pansare, R.; Yadav, G.; Nagare, M.R. Development of a structural framework to improve reconfigurable manufacturing system adoption in the manufacturing industry. *Int. J. Comput. Integr. Manuf.* **2023**, *36*, 349–380. [CrossRef]
26. Love, P.E.; Matthews, J.; Zhou, J. Is it just too good to be true? Unearthing the benefits of disruptive technology. *Int. J. Inf. Manag.* **2020**, *52*, 102096. [CrossRef]
27. Laskurain-Iturbe, I.; Arana-Landín, G.; Landeta-Manzano, B.; Uriarte-Gallastegi, N. Exploring the influence of industry 4.0 technologies on the circular economy. *J. Clean. Prod.* **2021**, *321*, 128944. [CrossRef]
28. Soori, M.; Arezoo, B.; Dastres, R. Internet of things for smart factories in industry 4.0, a review. *Internet ThingsCyber-Phys. Syst.* **2023**, *3*, 192–204. [CrossRef]
29. Ribeiro, J.; Lima, R.; Eckhardt, T.; Paiva, S. Robotic Process Automation and Artificial Intelligence in Industry 4.0—A Literature review. *Procedia Comput. Sci.* **2021**, *181*, 51–58. [CrossRef]
30. Muñoz-Saavedra, L.; Miró-Amarante, L.; Domínguez-Morales, M. Augmented and Virtual Reality Evolution and Future Tendency. *Appl. Sci.* **2020**, *10*, 322. [CrossRef]
31. Oesterreich, T.D.; Teuteberg, F. Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry. *Comput. Ind.* **2016**, *83*, 121–139. [CrossRef]
32. Astill, J.; Dara, R.A.; Fraser, E.D.; Roberts, B.; Sharif, S. Smart poultry management: Smart sensors, big data, and the internet of things. *Comput. Electron. Agric.* **2020**, *170*, 105291. [CrossRef]
33. Yu, K.; Lin, L.; Alazab, M.; Tan, L.; Gu, B. Deep Learning-Based Traffic Safety Solution for a Mixture of Autonomous and Manual Vehicles in a 5G-Enabled Intelligent Transportation System. *IEEE Trans. Intell. Transp. Syst.* **2021**, *22*, 4337–4347. [CrossRef]
34. Malik, S.; Muhammad, K.; Waheed, Y. Nanotechnology: A Revolution in Modern Industry. *Molecules* **2023**, *28*, 661. [CrossRef]
35. Mannering, F.; Bhat, C.R.; Shankar, V.; Abdel-Aty, M. Big data, traditional data and the tradeoffs between prediction and causality in highway-safety analysis. *Anal. Methods Accid. Res.* **2020**, *25*, 100113. [CrossRef]
36. Bello, S.A.; Oyedele, L.O.; Akinade, O.O.; Bilal, M.; Delgado, J.M.D.; Akanbi, L.A.; Ajayi, A.O.; Owolabi, H.A. Cloud computing in construction industry: Use cases, benefits and challenges. *Autom. Constr.* **2021**, *122*, 103441. [CrossRef]
37. Ferreira, W.d.P.; Armellini, F.; De Santa-Eulalia, L.A. Simulation in industry 4.0: A state-of-the-art review. *Comput. Ind. Eng.* **2020**, *149*, 106868. [CrossRef]
38. Corallo, A.; Lazoi, M.; Lezzi, M. Cybersecurity in the context of industry 4.0: A structured classification of critical assets and business impacts. *Comput. Ind.* **2020**, *114*, 103165. [CrossRef]

39. Morgan, J.; Halton, M.; Qiao, Y.; Breslin, J.G. Industry 4.0 smart reconfigurable manufacturing machines. *J. Manuf. Syst.* **2021**, *59*, 481–506. [CrossRef]
40. Jan, Z.; Ahamed, F.; Mayer, W.; Patel, N.; Grossmann, G.; Stumptner, M.; Kuusk, A. Artificial intelligence for industry 4.0: Systematic review of applications, challenges, and opportunities. *Expert Syst. Appl.* **2023**, *216*, 119456. [CrossRef]
41. Dalzochio, J.; Kunst, R.; Pignaton, E.; Binotto, A.; Sanyal, S.; Favilla, J.; Barbosa, J. Machine learning and reasoning for predictive maintenance in Industry 4.0: Current status and challenges. *Comput. Ind.* **2020**, *123*, 103298. [CrossRef]
42. Javaid, M.; Haleem, A.; Singh, R.P.; Khan, S.; Suman, R. Blockchain technology applications for Industry 4.0: A literature-based review. *Blockchain: Res. Appl.* **2021**, *2*, 100027. [CrossRef]
43. Haddud, A.; DeSouza, A.; Khare, A.; Lee, H. Examining potential benefits and challenges associated with the Internet of Things integration in supply chains. *J. Manuf. Technol. Manag.* **2017**, *28*, 1055–1085. [CrossRef]
44. Shrouf, F.; Ordieres, J.; Miragliotta, G. Smart factories in Industry 4.0: A review of the concept and of energy management approached in production based on the Internet of Things paradigm. In Proceedings of the 2014 IEEE International Conference on Industrial Engineering and Engineering Management, Selangor, Malaysia, 9–12 December 2014; pp. 697–701.
45. Busachi, A.; Erkoyuncu, J.; Colegrove, P.; Drake, R.; Watts, C.; Wilding, S. Additive manufacturing applications in Defence Support Services: Current practices and framework for implementation. *Int. J. Syst. Assur. Eng. Manag.* **2018**, *9*, 657–674. [CrossRef]
46. Stoltz, M.-H.; Giannikas, V.; McFarlane, D.; Strachan, J.; Um, J.; Srinivasan, R. Augmented Reality in Warehouse Operations: Opportunities and Barriers. *IFAC-PapersOnLine* **2017**, *50*, 12979–12984. [CrossRef]
47. Rodič, B. Industry 4.0 and the New Simulation Modelling Paradigm. *Organizacija* **2017**, *50*, 193–207. [CrossRef]
48. Castro-Martin, A.P.; Ahuett-Garza, H.; Guamán-Lozada, D.; Márquez-Alderete, M.F.; Coronado, P.D.U.; Castañon, P.A.O.; Kurfess, T.R.; de Castilla, E.G. Connectivity as a Design Feature for Industry 4.0 Production Equipment: Application for the Development of an In-Line Metrology System. *Appl. Sci.* **2021**, *11*, 1312. [CrossRef]
49. Pereira, T.; Barreto, L.; Amaral, A. Network and information security challenges within Industry 4.0 paradigm. *Procedia Manuf.* **2017**, *13*, 1253–1260. [CrossRef]
50. Villar, L.M.-D.; Oliva-Lopez, E.; Luis-Pineda, O.; Benešová, A.; Tupa, J.; Garza-Reyes, J. Fostering economic growth, social inclusion & sustainability in Industry 4.0: A systemic approach. *Procedia Manuf.* **2020**, *51*, 1755–1762. [CrossRef]
51. Malek, J.; Desai, T.N. A systematic literature review to map literature focus of sustainable manufacturing. *J. Clean. Prod.* **2020**, *256*, 120345. [CrossRef]
52. 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]
53. Ching, N.T.; Ghobakhloo, M.; Iranmanesh, M.; Maroufkhani, P.; Asadi, S. Industry 4.0 applications for sustainable manufacturing: A systematic literature review and a roadmap to sustainable development. *J. Clean. Prod.* **2022**, *334*, 130133. [CrossRef]
54. Qi, Q.; Xu, Z.; Rani, P. Big data analytics challenges to implementing the intelligent Industrial Internet of Things (IIoT) systems in sustainable manufacturing operations. *Technol. Forecast. Soc. Chang.* **2023**, *190*, 122401. [CrossRef]
55. Ghobakhloo, M.; Iranmanesh, M.; Morales, M.E.; Nilashi, M.; Amran, A. Actions and approaches for enabling Industry 5.0-driven sustainable industrial transformation: A strategy roadmap. *Corp. Soc. Responsib. Environ. Manag.* **2023**, *30*, 1473–1494. [CrossRef]
56. Epstein, M.J.; Elkington, J.; Leonard, H.B. Making Sustainability Work: Best Practices in Managing and Measuring Corporate Social, Environmental and Economic Impacts. In *Making Sustainability Work*; Taylor & Francis Ltd.: London, UK, 2018.
57. Panwar, R.; Rinne, T.; Hansen, E.; Juslin, H. Corporate responsibility: Balancing economic, environmental, and social issues in the forest products industry. *For Prod. J.* **2006**, *56*, 4–13.
58. 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]
59. Aggerholm, H.K.; Andersen, S.E.; Thomsen, C. Conceptualising employer branding in sustainable organisations. *Corp. Commun. Int. J.* **2011**, *16*, 105–123. [CrossRef]
60. Herrmann, C.; Schmidt, C.; Kurle, D.; Blume, S.; Thiede, S. Sustainability in manufacturing and factories of the future. *Int. J. Precis. Eng. Manuf.-Green Technol.* **2014**, *1*, 283–292. [CrossRef]
61. Foo, D.C.; Tan, R.R. A review on process integration techniques for carbon emissions and environmental footprint problems. *Process. Saf. Environ. Prot.* **2016**, *103*, 291–307. [CrossRef]
62. Bithas, K. The sustainable residential water use: Sustainability, efficiency and social equity. The European experience. *Ecol. Econ.* **2008**, *68*, 221–229. [CrossRef]
63. Kurapatskie, B.; Darnall, N. Which Corporate Sustainability Activities are Associated with Greater Financial Payoffs? *Bus. Strat. Environ.* **2013**, *22*, 49–61. [CrossRef]
64. Chatterjee, S.; Chaudhuri, R.; Vrontis, D.; Dana, L.-P.; Kabbara, D. Developing resilience of MNEs: From global value chain (GVC) capability and performance perspectives. *J. Bus. Res.* **2024**, *172*, 114447. [CrossRef]
65. Yong, J.Y.; Yusliza, M.Y.; Ramayah, T.; Chiappetta Jabbour, C.J.; Sehnem, S.; Mani, V. Pathways towards sustainability in manufacturing organizations: Empirical evidence on the role of green human resource management. *Bus. Strategy Environ.* **2020**, *29*, 212–228. [CrossRef]

66. Mabkhot, M.M.; Ferreira, P.; Maffei, A.; Podržaj, P.; Mądziel, M.; Antonelli, D.; Lanzetta, M.; Barata, J.; Boffa, E.; Finžgar, M.; et al. Mapping Industry 4.0 Enabling Technologies into United Nations Sustainability Development Goals. *Sustainability* **2021**, *13*, 2560. [CrossRef]
67. Stefanini, R.; Vignali, G. The influence of Industry 4.0 enabling technologies on social, economic and environmental sustainability of the food sector. *Int. J. Prod. Res.* **2023**, *13*, 150. [CrossRef]
68. Mittal, S.; Khan, M.A.; Romero, D.; Wuest, T. Smart manufacturing: Characteristics, technologies and enabling factors. *Proc. Inst. Mech. Eng. B J. Eng. Manuf.* **2019**, *233*, 1342–1361. [CrossRef]
69. Nižetić, S.; Šolić, P.; González-de-Artaza, D.L.-d.I.; Patrono, L. Internet of Things (IoT): Opportunities, issues and challenges towards a smart and sustainable future. *J. Clean. Prod.* **2020**, *274*, 122877. [CrossRef] [PubMed]
70. Dzedzickis, A.; Subačiūtė-Žemaitienė, J.; Šutinys, E.; Samukaitė-Bubnienė, U.; Bučinskas, V. Advanced Applications of Industrial Robotics: New Trends and Possibilities. *Appl. Sci.* **2021**, *12*, 135. [CrossRef]
71. Javaid, M.; Haleem, A.; Singh, R.P.; Suman, R.; Rab, S. Role of additive manufacturing applications towards environmental sustainability. *Adv. Ind. Eng. Polym. Res.* **2021**, *4*, 312–322. [CrossRef]
72. Sousa, N.; Jorge, F.; Teixeira, M.S.; Losada, N.; Melo, M.; Bessa, M. An Exploratory Study about the Effect of COVID-19 on the Intention to Adopt Virtual Reality in the Tourism Sector. *Sustainability* **2023**, *15*, 8725. [CrossRef]
73. Zizic, M.C.; Mladineo, M.; Gjeldum, N.; Celent, L. From Industry 4.0 towards Industry 5.0: A Review and Analysis of Paradigm Shift for the People, Organization and Technology. *Energies* **2022**, *15*, 5221. [CrossRef]
74. Todd, R.; Allen, D.; Alting, L. *Fundamental Principles of Manufacturing Processes*; Industrial Press, Inc.: New York, NY, USA, 1994.
75. Valivullah, L.; Mani, M.; Lyons, K.W.; Gupta, S.K. Manufacturing Process Information Models for Sustainable Manufacturing. In Proceedings of the ASME 2014 International Manufacturing Science and Engineering Conference, MSEC 2014 Collocated with the JSME 2014 International Conference on Materials and Processing and the 42nd North American Manufacturing Research Conference, Detroit, MI, USA, 9–13 June 2014; Volume 1.
76. Mani, M.; Madan, J.; Lee, J.H.; Lyons, K.W.; Gupta, S. Sustainability characterisation for manufacturing processes. *Int. J. Prod. Res.* **2014**, *52*, 5895–5912. [CrossRef]
77. Mani, M.; Madan, J.; Lee, J.H.; Lyons, K.; Gupta, S.K. Characterizing Sustainability for Manufacturing Performance Assessment. In Proceedings of the ASME Design Engineering Technical Conference, Chicago, IL, USA, 17 August 2012; Volume 2, pp. 1153–1162.
78. Haapala, K.R.; Zhao, F.; Camelio, J.; Sutherland, J.W.; Skerlos, S.J.; Dornfeld, D.A.; Jawahir, I.S.; Clarens, A.F.; Rickli, J.L. A review of engineering research in sustainable manufacturing. *J. Manuf. Sci. Eng.* **2013**, *135*, 041013. [CrossRef]
79. Wang, J.-J.; Jing, Y.-Y.; Zhang, C.-F.; Zhao, J.-H. Review on multi-criteria decision analysis aid in sustainable energy decision-making. *Renew. Sustain. Energy Rev.* **2009**, *13*, 2263–2278. [CrossRef]
80. Siksnelyte, I.; Zavadskas, E.K.; Streimikiene, D.; Sharma, D. An Overview of Multi-Criteria Decision-Making Methods in Dealing with Sustainable Energy Development Issues. *Energies* **2018**, *11*, 2754. [CrossRef]
81. Kibira, D.; Brundage, M.P.; Feng, S.; Morris, K.C. Procedure for Selecting Key Performance Indicators for Sustainable Manufacturing. *J. Manuf. Sci. Eng.* **2018**, *140*, 011005. [CrossRef]
82. Dornelles, J.d.A.; Ayala, N.F.; Frank, A.G. Smart Working in Industry 4.0: How digital technologies enhance manufacturing workers' activities. *Comput. Ind. Eng.* **2022**, *163*, 107804. [CrossRef]
83. Breque, M.; De Nul, L.; Petridis, A. Industry 5.0: Towards a sustainable, human-centric and resilient European industry. In *European Commission, Directorate-General for Research and Innovation*; European Commission: Brussels, Belgium, 2021.
84. Dwivedi, A.; Agrawal, D.; Jha, A.; Mathiyazhagan, K. Studying the interactions among Industry 5.0 and circular supply chain: Towards attaining sustainable development. *Comput. Ind. Eng.* **2023**, *176*, 108927. [CrossRef]
85. Gajdzik, B.; Grabowska, S.; Saniuk, S.; Wieczorek, T. Sustainable development and industry 4.0: A bibliometric analysis identifying key scientific problems of the sustainable industry 4.0. *Energies* **2020**, *13*, 4254. [CrossRef]
86. Golovianko, M.; Terziyan, V.; Branytskyi, V.; Malyk, D. Industry 4.0 vs. Industry 5.0: Co-existence, Transition, or a Hybrid. *Procedia Comput. Sci.* **2023**, *217*, 102–113. [CrossRef]
87. Xu, X.; Lu, Y.; Vogel-Heuser, B.; Wang, L. Industry 4.0 and Industry 5.0—Inception, conception and perception. *J. Manuf. Syst.* **2021**, *61*, 530–535. [CrossRef]
88. Friedman, B.; Kahn, P.H., Jr. Human values, ethics, and design. In *The Human-Computer Interaction Handbook*; CRC Press: Boca Raton, FL, USA, 2007; pp. 1267–1292. [CrossRef]
89. Khalid, A.; Kirisci, P.; Ghrairi, Z.; Thoben, K.-D.; Pannek, J. A methodology to develop collaborative robotic cyber physical systems for production environments. *Logist. Res.* **2016**, *9*, 23. [CrossRef]
90. Zebrowski, C. The value of resilience: Securing life in the twenty-first century. In *The Value of Resilience: Securing Life in the Twenty-First Century*; Taylor & Francis Ltd.: London, UK, 2015; pp. 1–160.
91. Ghobakhloo, M.; Iranmanesh, M.; Foroughi, B.; Tirkolaee, E.B.; Asadi, S.; Amran, A. Industry 5.0 implications for inclusive sustainable manufacturing: An evidence-knowledge-based strategic roadmap. *J. Clean. Prod.* **2023**, *417*, 138023. [CrossRef]
92. Schmitt, T.; Wolf, C.; Lennerfors, T.T.; Okwir, S. Beyond "Leanear" production: A multi-level approach for achieving circularity in a lean manufacturing context. *J. Clean. Prod.* **2021**, *318*, 128531. [CrossRef]
93. Ahmed, A.; Bhatti, S.H.; Gölgeci, I.; Arslan, A. Digital platform capability and organizational agility of emerging market manufacturing SMEs: The mediating role of intellectual capital and the moderating role of environmental dynamism. *Technol. Forecast. Soc. Chang.* **2022**, *177*, 121513. [CrossRef]

94. Mukherjee, A.A.; Raj, A.; Aggarwal, S. Identification of barriers and their mitigation strategies for industry 5.0 implementation in emerging economies. *Int. J. Prod. Econ.* **2023**, *257*, 108770. [CrossRef]
95. Sinsel, S.R.; Riemke, R.L.; Hoffmann, V.H. Challenges and solution technologies for the integration of variable renewable energy sources—A review. *Renew. Energy* **2020**, *145*, 2271–2285. [CrossRef]
96. Cillo, V.; Gregori, G.L.; Daniele, L.M.; Caputo, F.; Bitbol-Saba, N. Rethinking companies' culture through knowledge management lens during Industry 5.0 transition. *J. Knowl. Manag.* **2022**, *26*, 2485–2498. [CrossRef]
97. Leng, J.; Sha, W.; Lin, Z.; Jing, J.; Liu, Q.; Chen, X. Blockchained smart contract pyramid-driven multi-agent autonomous process control for resilient individualised manufacturing towards Industry 5.0. *Int. J. Prod. Res.* **2023**, *61*, 4302–4321. [CrossRef]
98. Destouet, C.; Tlahig, H.; Bettayeb, B.; Mazari, B. Flexible job shop scheduling problem under Industry 5.0: A survey on human reintegration, environmental consideration and resilience improvement. *J. Manuf. Syst.* **2023**, *67*, 155–173. [CrossRef]
99. Ghobakhloo, M.; Iranmanesh, M.; Tseng, M.-L.; Grybauskas, A.; Stefanini, A.; Amran, A. Behind the definition of Industry 5.0: A systematic review of technologies, principles, components, and values. *J. Ind. Prod. Eng.* **2023**, *40*, 432–447. [CrossRef]
100. Yin, S.; Yu, Y. An adoption-implementation framework of digital green knowledge to improve the performance of digital green innovation practices for industry 5.0. *J. Clean. Prod.* **2022**, *363*, 132608. [CrossRef]
101. Wang, H.; Lv, L.; Li, X.; Li, H.; Leng, J.; Zhang, Y.; Thomson, V.; Liu, G.; Wen, X.; Sun, C.; et al. A safety management approach for Industry 5.0′s human-centered manufacturing based on digital twin. *J. Manuf. Syst.* **2023**, *66*, 1–12. [CrossRef]
102. Grybauskas, A.; Stefanini, A.; Ghobakhloo, M. Social sustainability in the age of digitalization: A systematic literature Review on the social implications of industry 4.0. *Technol. Soc.* **2022**, *70*, 101997. [CrossRef]
103. Esmaeilian, B.; Behdad, S.; Wang, B. The evolution and future of manufacturing: A review. *J. Manuf. Syst.* **2016**, *39*, 79–100. [CrossRef]
104. Szum, K.; Nazarko, J. Exploring the Determinants of Industry 4.0 Development Using an Extended SWOT Analysis: A Regional Study. *Energies* **2020**, *13*, 5972. [CrossRef]
105. Stock, T.; Obenaus, M.; Kunz, S.; Kohl, H. Industry 4.0 as enabler for a sustainable development: A qualitative assessment of its ecological and social potential. *Process Saf. Environ. Prot.* **2018**, *118*, 254–267. [CrossRef]
106. Bai, C.; Dallasega, P.; Orzes, G.; Sarkis, J. Industry 4.0 technologies assessment: A sustainability perspective. *Int. J. Prod. Econ.* **2020**, *229*, 107776. [CrossRef]
107. Manoharan, S.; Haapala, K.R. A Grey Box Software Framework for Sustainability Assessment of Composed Manufacturing Processes: A Hybrid Manufacturing Case. *Procedia CIRP* **2019**, *80*, 440–445. [CrossRef]
108. Agote-Garrido, A.; Martín-Gómez, A.M.; Lama-Ruiz, J.R. Industry 5.0 Values. A bibliometric analysis of the new industrial paradigm from the social approach. *DYNA* **2023**, *98*, 531–536. [CrossRef]
109. Dermol, V.; Širca, N.T. Communication, Company Mission, Organizational Values, and Company Performance. *Procedia-Soc. Behav. Sci.* **2018**, *238*, 542–551. [CrossRef]
110. Hendry, D.G.; Friedman, B.; Ballard, S. Value sensitive design as a formative framework. *Ethic-Inf. Technol.* **2021**, *23*, 39–44. [CrossRef]
111. Van Der Hoven, J.; Manders-Huits, N. Value-sensitive Design. In *The Ethics of Information Technologies*; Routledge: London, UK, 2020; pp. 329–332. [CrossRef]