systems

MDPI

Article

Manufacturing System Design in Industry 5.0: Incorporating Sociotechnical Systems and Social Metabolism for Human-Centered, Sustainable, and Resilient Production

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

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

Abstract: This paper delves into the concept of social metabolism as a foundation for the development of sociotechnical systems in Industry 5.0. The study conducts an analysis of the existing methods and approaches for designing sociotechnical systems, and reviews publications that utilize such systems to incorporate Industry 4.0 technologies into manufacturing processes. Additionally, it examines the three key factors of Industry 5.0 and the enabling framework of Industry 4.0 technologies. Based on these investigations, a theoretical model is proposed for manufacturing system design, employing sociotechnical systems to integrate Industry 4.0 enabling technologies, while considering the essential aspects of Industry 5.0. The model emphasizes the early consideration of sociotechnical systems to design manufacturing systems that prioritize human-centricity, sustainability, and resilience. By embracing this comprehensive approach, the proposed model contributes to the realization of a production environment aligned with societal needs, fostering a more conscious and adaptable industry.

Keywords: Industry 5.0; sociotechnical system; social metabolism; human-centered; sustainable; resilient; manufacturing system design; adaptable industry

check for updates

Citation: 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. https://doi.org/10.3390/systems11110537

Academic Editors: Michael E. Miller and Christina Rusnock

Received: 25 September 2023
Revised: 1 November 2023
Accepted: 3 November 2023
Published: 4 November 2023

1. Introduction

Social metabolism stands as a key concept in industrial ecology [1]. It examines the interactions between humans and the environment, focusing on the flows of energy and materials stemming from socio-economic activities. This perspective enables an understanding of how human actions are interconnected with ecological processes, aiming to find sustainable approaches that reduce environmental impact [2]. Within the context of sociotechnical systems, comprehending social metabolism facilitates the design of smart and sustainable manufacturing systems [3].

Sociotechnical systems, in their relation to social metabolism, address the intricate interplay between social and technical elements within an organizational context [4]. This approach aims to balance technical efficiency and the well-being of workers [5]. Industry 5.0 emerges as an evolution of Industry 4.0 [6]. This new paradigm focuses on integrating advanced technologies derived from its predecessor, such as artificial intelligence, robotics, or the Internet of Things, with a human-centered, sustainable, and resilient approach [7]. This industrial model seeks to create symbiotic factories where productive efficiency is optimized, ensuring a safe and healthy work environment.

There are many questions that arise regarding the new era of Industry 5.0, the development of value-based work environments, and the potential integration of sociotechnical theory to mitigate the imbalance between industrial activity and natural systems. The disconnect between industrial economy and natural cycles is referred to as metabolic rift [8]. Therefore, this paper addresses the following research questions (RQs): (RQ1) Is it possible to define strategies guided by the values of the new industrial paradigm and sociotechnical theory that reverse the metabolic rift? (RQ2) What is a suitable framework that enables industrial sustainability at different levels of analysis? (RQ3) What knowledge, tools, and techniques should be integrated into the proposed model for enabling technologies of sociotechnical systems to develop from the values of Industry 5.0?

This paper stands out for several fundamental contributions in the field of manufacturing systems and Industry 5.0, especially through the conceptualization of sociotechnical systems within the framework of social metabolism. One of the main contributions of this research is the formulation of a theoretical model for sociotechnical systems, which not only integrates the fundamental principles of social metabolism but also considers the technologies of modern production systems. This innovative approach allows for the design of manufacturing systems that are not only technically efficient but also promote environmental sustainability and human well-being. Furthermore, by proposing a model that emphasizes the adoption of enabling technologies under the Industry 5.0 paradigm, this paper sets a precedent for the conscious integration of sustainability and resilience at the core of industrial systems. This provides a valuable roadmap not only for theoretical transformation but also for the practical overhaul of current production systems toward structures that prioritize social, environmental, and human needs.

In relation to the above, the following objectives can be formulated based on the theme of study: (1) Defining the values of the new industrial paradigm to consider them at the early stages of enabling technology design. (2) Identifying sociotechnical systems and their principles. (3) Incorporating activity theory (AT) into the conception of industrial environments to mitigate the metabolic rift. (4) Proposing a framework for integrating enabling technologies of sociotechnical systems from the values of Industry 5.0.

Given the objectives to develop, this paper is organized as follows: (1) Introduction: it defines the problem and what is expected from the research. (2) Social metabolism and sociotechnical systems: it defines their principles and how they relate. (3) Industry 4.0 technologies: it analyzes the advantages and disadvantages of enabling technologies for sociotechnical systems. (4) Industry 5.0: it defines the new industrial paradigm. (5) Design model: it proposes a theoretical model to integrate Industry 5.0 values into a production process. (6) Conclusions after the research.

2. Social Metabolism and Sociotechnical Systems

2.1. Social Metabolism

Global physical constraints require a paradigm that studies human interactions and designs adaptation strategies. This approach, defined as the set of all flows and transformations of physical resources in a systems context, is called social metabolism [9]. The concept of social metabolism encompasses the extraction of natural resources, their transformation into production, their accumulation, and their release as waste and emissions [10]. The relationship between social metabolism and its fundamental aspects of organization motivates research into changes in social structures [11].

The current concept of sustainability pertains to the ecological limitations of the planet and the interference that human activities have with these boundaries [12]. A sustainable and resilient state requires social changes. These can be understood as transformations of sociotechnical systems [13]. Considering sociotechnical systems in relation to social metabolism involves distinguishing three types of systematic impacts on the biophysical sphere: positive, neutral, and negative impacts. Positive impacts aim to enable ecological resilience [14]. Neutral impacts maintain human well-being and fulfill the basic requirements of stakeholders [15]. Finally, negative impacts exert additional pressure on planetary boundaries [12].

2.2. Sociotechnical Systems: Principles

Current organizations constitute complex systems. The study of complex systems employs complexity science [16]. This way of thinking assumes that a system can be understood through the interactions between its various parts, not just its internal elements but also the connections and interdependencies between systems. Under this premise, sociotechnical theory emerges [17]. This thinking is based on the idea that design is systematic and requires the consideration of both social and technical factors. This term was originally used to denote human–machine interaction in the industrial workplace [18]. However, in 1960, Emery and Trist expanded its scope to describe systems involving complex interactions between technology and humans, as well as their consequences [4]. The sociotechnical approach continues to seek the joint optimization of social and technical systems. The technical system encompasses technology and its associated work structure, while the social system refers to groups of individuals and the coordination, control, and management of boundaries [19]. Badham et al. identify five fundamental characteristics of sociotechnical systems [20]. Systems must have independent parts, they should be adaptive, they possess an internal environment composed of technical and social subsystems, system objectives can be achieved via multiple means, and system performance relies on joint optimization [19].

2.3. Key Approaches and Methods

Sociotechnical design emerged at the Tavistock Institute in London. At the time, there was widespread job dissatisfaction among lower-ranking workers engaged in routine tasks with limited opportunities for personal development [21]. Bertalanffy introduced the notion of "open systems". He suggested that systems become increasingly complex but ultimately reach a state of stability that allows them to adapt to change [22]. Fred Emery developed the concept of "function redundancy". He proposed that individuals should have the ability to perform various tasks to cope with unexpected events [19]. Herbst developed the concept of "minimal critical specifications" [23]. He rejects the idea that jobs should be over-specified. Workers should know what to do, but they should not be told how to do it.

Figure 1 presents the nine sociotechnical design principles proposed by Albert Cherns [24]: (i) Compatibility: the design process must align with its objectives. (ii) Minimum critical specification: social groups should have clear objectives, but they should decide how to achieve them. (iii) Sociotechnical criteria: deviations from expected norms and standards should be eliminated or controlled. (iv) Multifunctionality principle: groups need a variety of skills to be able to respond to changes. (v) Boundary locations should facilitate the exchange of knowledge and experiences. All groups should learn from each other. (vi) Information should be transmitted to where it is needed for action. (vii) Supporting congruence: social support systems that reinforce desired behavior should be designed. (viii) Design and human values: quality work requires opportunities that lead to a desirable future. (ix) Incomplete establishes that design is an iterative process that never stops.

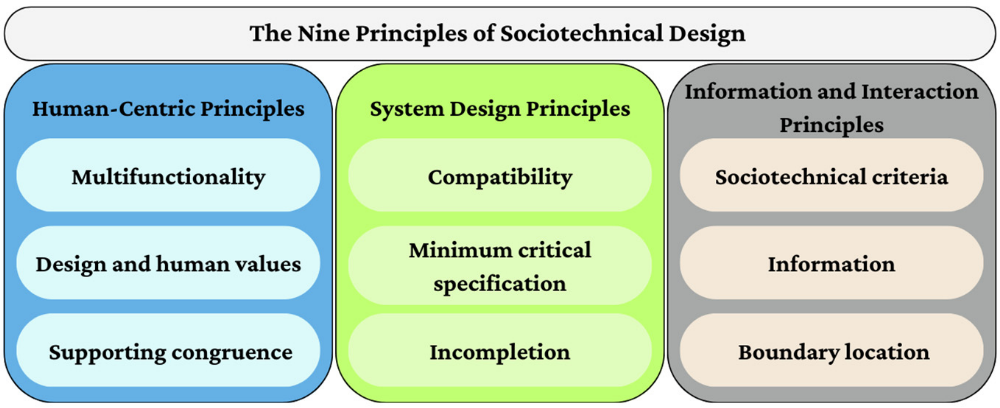

Figure 1. The nine principles of sociotechnical design.

2.4. Activity Theory

Activity theory is a theoretical framework developed by Lev Vygotsky and later expanded upon by other researchers such as Aleksandr Luria and Alexei Leontiev [25]. This framework has been widely used to understand how human activities relate to technical aspects within a system [26]. Activity theory provides a structure for understanding technical and social interactions. Furthermore, it allows for the design of sociotechnical systems by identifying areas for enhancement [27]. Leontiev represents activity theory using a model with six vertices. The subject is the primary actor who performs an activity. The object is what the subject intends to achieve through the development of the activity. The tool is any technology, physical or virtual, that the subject uses to carry out the activity. The community represents the social context. Rules encompass all the norms and procedures that guide the activity. Finally, the division of labor considers the roles within the community and how tasks are distributed [28].

2.5. Other Sociotechnical Approaches

In addition to the identified sociotechnical systems approaches and principles, there are other approaches that encompass sociotechnical ideas. The study and consideration of these other approaches will assist in the development of intelligent social manufacturing systems. Soft Systems Methodology (SSM) is an approach that considers the roles, responsibilities, and concerns of stakeholders. Its objective is to understand problems from the perspectives of those involved [29]. Cognitive Work Analysis (CWA) is a formative approach based on predicting the operation of complex systems. This approach contrasts with most approaches, which are either normative (establishing how work should be carried out) or descriptive (establishing how work is carried out) [30]. The socio-technical method for designing work systems is designed for use in job allocation. It identifies tasks that should be assigned to machines and considers those that should be performed by humans [31]. Ethnographic workplace analysis focuses on measuring operational problems that affect system functionality and use. It highlights the importance of workplace awareness [32]. Contextual design is based on the idea that any system inherently incorporates a particular way of working that then characterizes how it will be structured. Its aim is to design products based on how the customer performs work [33]. Cognitive systems engineering analyzes organizational issues. It uses observation as a tool to understand sources of failure [34]. Human-centered design considers social and cultural factors. It is based on an explicit understanding of users, their tasks, and their environment [35].

2.6. Metabolic Rift

The approach that sociotechnical theory has had up to the present has driven industrialization. Increasing industrial capital has allowed for growing economic development [36]. However, this conception of sociotechnical systems has led to natural capital and social capital becoming increasingly separated. As Figure 2 depicts, the concept of metabolic rift refers to the imbalance in the flows of materials, energy, and resources in the manufacturing sector. The waste of resources, excessive energy consumption, or the disconnection of processes are some of the ways in which the metabolic rift that the industrial environment has undergone is manifested. This raises the need to reconsider how sociotechnical systems are designed and managed [37].

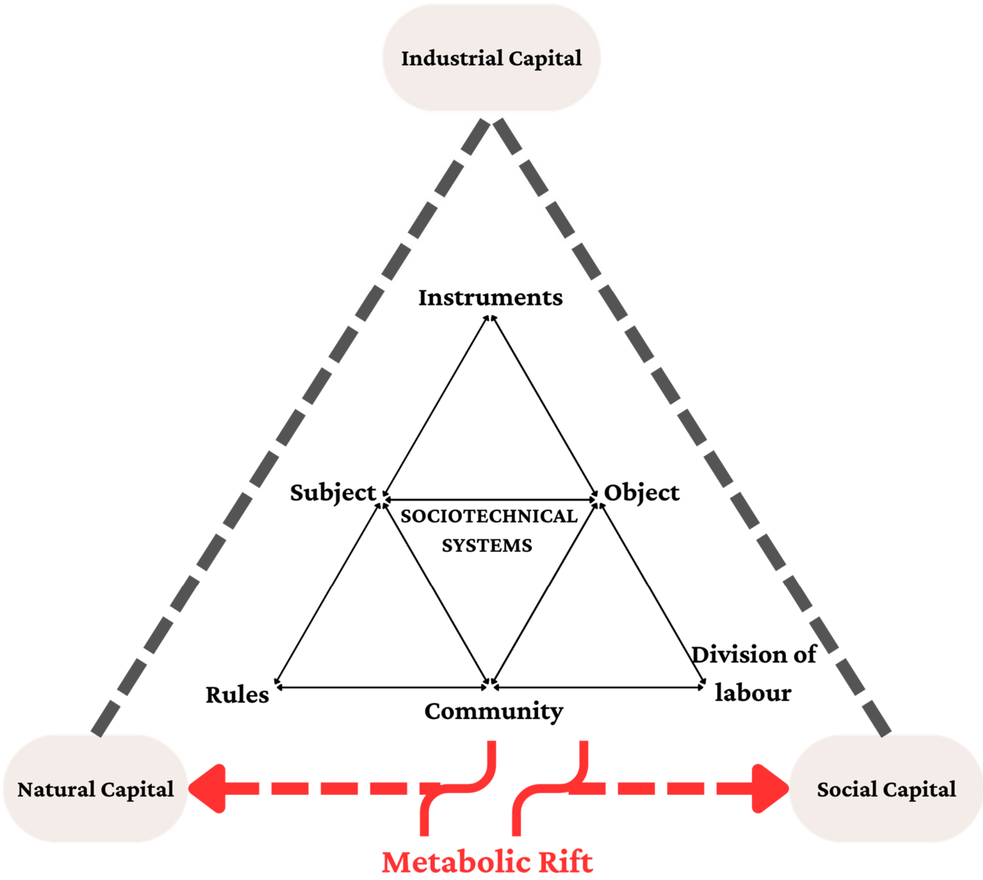

Figure 2. Metabolic rift between social capital and natural capital.

3. Incorporation of Industry 4.0 and Enabling Technologies into Manufacturing Systems

Modern factories are currently in the process of adapting to the new era of interconnectivity and digitization, known as the Fourth Industrial Revolution [38]. These factories are employing advanced technologies to enhance manufacturing productivity, response time, and profitability [39]. However, the implementation of these machines alongside workers has created highly complex production environments. The development of these environments aims to prevent workers from performing hazardous, monotonous, or demeaning tasks, elevating them to tasks requiring skill and critical thinking that would be difficult to automate or replace [40]. However, research has predominantly focused on technological advancement, with minimal attention given to the integration of workers into these intelligent systems [41].

3.1. Industry 4.0 Technologies

The development of advanced technologies has enabled the advancement of integrated and connected systems capable of monitoring equipment, collecting a large amount of data, and updating virtual models with information from physical processes. This leads to a new era of smart manufacturing [42]. However, rapid technological development leads to the impact of enabling technologies on sociotechnical systems not always being positive. Table 1 summarizes the positive and negative aspects of some enabling technologies during Industry 4.0. The main positive impacts are the improvement of worker safety and health, time reduction, training effectiveness, waste reduction, and easy access to real-time information about activities [43]. On the other hand, the main negative impacts of technologies in manufacturing activities are worker resistance, the discomfort of devices, and a high level of required technical skills [44].

Table 1. Positive and negative impacts of enabling 4.0 technologies.

Technology	Positive Impacts	Negative Impacts
Augmented Reality	Improved training, effective worker supervision, error reduction, reduced cognitive load, enhanced safety, decision support, and improved information exchange	Visual fatigue, distractions during use, user resistance, device weight and discomfort, job impoverishment, increased stress
Virtual Reality	Aids in executing operations, reduces costs, enhances cognitive abilities, eliminates the need for written documents	Decreases the decision-making capacity of workers, incompatibility with some safety equipment, impairs visual acuity, compromises the field of vision and vision
Autonomous Robots	Increased productivity, reduced human effort, reduced mental and physical stress, reduced occupational health risks, better production process monitoring, improved product quality, increased job attractiveness	Replacement of some workers, dependence on the proper functioning of robotic systems, increased complexity of activities, difficulty in worker acceptance
Cobots	Simplifies tasks, improves productivity, enhances operational safety, reduces errors, decreases manual labor, assists workers with physical disabilities	Collision control problems, safety and ergonomic issues, increased anxiety, problems with handling deformable objects, slowness due to legislation and safety concerns
Wearables	Real-time location of workers, improved workplace safety, enhanced working conditions, assistance in time and quality measurement, increased awareness of ergonomics	Privacy data concerns, data integration issues, difficulty adapting to different body types, psychophysical measurement can be invasive
Artificial Intelligence	Reduced downtime, reduced failures, reduced training costs	Limited trust from workers, ethical concerns
Digital Twins	Aids in operation planning, minimizes the impact of disruptions, enhances daily task efficiency, reduces maintenance costs, optimizes resources	Difficulty in managing unexpected disruptions, challenges in data management and analysis, cyberattacks can steal industrial knowledge
Cloud Computing	Reduces the incidence of recurring issues, drives the continuous improvement process	Possible issues with knowledge sharing, concerns about protecting corporate intelligence
Internet of Things (IoT)	More efficient production, improved coordination between units, waste reduction, facilitates real-time data recognition and analysis, generates knowledge for continuous process improvement and optimization	Resistance from workers to change, complexity, usability, and acceptability can be challenging, concerns about system security

Authors like Hendrick and Kleiner acknowledge that the adoption of this technologies, emerging from Industry 4.0, is not sustainable on its own from a sociotechnical perspective. At least three complementary sociotechnical dimensions must be considered: first, work organization, since new technologies demand a reevaluation of how the organization will operate [45]; second, the human factor, as new technologies require skills and competencies from the workforce [46]; finally, external context, as new technologies are influenced by the maturity of the environment in which they are applied [47].

3.2. Sociotechnical Theory in Advanced Manufacturing Systems

Sociotechnical systems theory considers that a change in one part of the system results in changes in the other [48]. Current manufacturing systems are characterized by the implementation of Cyber–Physical Systems (CPS) to enhance human abilities. Therefore, the symbiotic relationship to achieve in manufacturing systems in the context of Industry 5.0 also has a human (social) and a technological (technical) part [49]. One of the most used frameworks when considering sociotechnical systems is the one proposed by Leavitt [50]. This focuses on the relationships between four dimensions: people, tasks, structure, and technologies. Later, this framework was extended to six dimensions: people, infrastructure, technologies, culture, processes, and goals [51].

A working system will typically have a set of objectives, involve different individuals (with various skills and attitudes), employ various technologies, make use of infrastructure, and operate with cultural assumptions. Additionally, the system will exist within a broader context, including regulatory frameworks, different stakeholders, and a surrounding economic and financial environment. This framework provides a way to analyze the links between different social and technical aspects. The value of this approach lies in its ability to offer a systematic and structured way of analyzing a variety of systems [48].

3.2.1. Sustainability

Recent studies have shown the potential of merging the sociotechnical systems approach with socioecological systems to advance toward the development of sustainable systems [52]. The concept of sociotechnical ecology is proposed by Hägerstrand. This approach aims to advance the understanding of how humans, technology, and nature coexist [53]. Advancing toward more sustainable solutions requires structural changes in established systems. These changes are often triggered by policies that allow for the reconfiguration of the market. Hoppmann suggests that a constant realignment of policies with changing sociotechnical system conditions is necessary [54]. Lauber and Jacobsson demonstrate how changes in the sociotechnical system influence different actors in a renewable energy environment [55]. Currently, the interaction between technological change, politics, and regulatory processes remains understudied. Additionally, these papers only cover a single instrument rather than a broader combination.

3.2.2. Resilience

Advanced manufacturing systems encompass various processes that can be affected by a variety of unforeseen factors. These unforeseen factors can include supply chain disruptions, changes in market demand, or natural disasters [56]. The term resilience not only refers to the ability of a system to recover from disruptions but also its ability to adapt and continue to operate effectively [57]. The implementation of resilience in manufacturing systems begins with the design of robust systems that consider strategic redundancy and flexibility. Furthermore, it is important to consider other aspects such as strategic management to identify potential scenarios and establish contingency plans. Finally, it is necessary to make use of existing technology. Solutions like artificial intelligence or real-time monitoring can help detect early problems and make decisions [58].

3.2.3. Current Research Trends

The development of Cyber–Physical Systems (CPS) based on sociotechnical theory is of increasing interest due to the emerging Industry 5.0 and its values. CPS integrates physical and computational systems to enhance process management and connectivity [59]. However, cutting-edge research also acknowledges that factories have a human component that should not be overlooked. This leads to the emergence of the term Human–Cyber–Physical Systems (HCPS). Another line of research based on sociotechnical theory is associated with digital twins (DTs). The aim of this line of research is to achieve a better digital representation of the human factor [60]. This development is called the human digital twin (HDT). The literature already reflects research on the modeling of digital twins of organizations and entire systems in contexts such as smart cities, for example. There are also studies presented that consider digital twins in production processes. In all these situations, spaces are defined where the people, organizations, and physical objects involved are reflected at a virtual level.

4. Industry 5.0 Approaches

Industry 5.0 emerges in response to the need to develop industrial processes centered on the principles of social justice and sustainability. This new industrial paradigm is based on socially and environmentally relevant values [61]. It has three main objectives [62]. First, it aims to integrate the technologies developed during the Fourth Industrial Revolution with human skills and strengths. Additionally, it seeks to ensure environmental sustainability without compromising the limits of the planet. Finally, it aims to establish a resilient vision that promotes industry prosperity [7].

Currently, there are various definitions to understand this fifth revolutionary wave [63,64]. Researchers like Romero and Müller agree that this paradigm shift does not emerge to replace Industry 4.0. Instead, it presents itself as an enhanced version of Industry 4.0 [65]. Table 2 compares the main aims and approaches between Industry 4.0 and Industry 5.0 [58,66]. It aims to develop a hyperconnected industrial ecosystem driven by values to achieve sustainable development aims (SDGs) [67].

Table 2. Key differences between Industry 4.0 and Industry 5.0.

	Industry 4.0	**Industry 5.0**
Objectives	Intelligent and interconnected production process. System optimization.	Social benefit. Human-centric. Sustainability. Environmental care. Sustainability. Resource management.
Human Factor	Human–machine interaction. Human reliability.	Ethical use of technology to promote human values and needs. Worker management and safety.
Environment	Higher material consumption. Higher energy consumption.	Awareness and waste recycling. Renewable energy sources.
Resilience	Automatic fault detection. Autonomous decision-making.	Human adaptation to unexpected situations. Interoperability.

4.1. Adapting Technology to Humans

Industry 5.0 promotes collaboration between human experts and intelligent machinery but shifts the perspective from Industry 4.0 [68]. Industry 5.0 focuses on mass customization, where humans guide the integration of technology into production systems. It is designed to enhance the satisfaction of all human parties involved in the processes [69]. Classical studies by Taylor in the development of sociotechnical systems were based on the idea of adapting workers to the characteristics of machines to achieve maximum production efficiency [70]. However, Industry 5.0 changes the approach to conceptualizing a sociotechnical system. In the new industrial paradigm, it is technology that is sought to be adapted to the needs of humans [71].

4.2. Technology for Environmental Sustainability

Technological innovation in Industry 5.0 is oriented toward supporting socio-environmental development [61]. The European Commission, in its Industry 5.0 agenda [7], emphasizes that for industry to be sustainable, it must prioritize emerging socio-environmental needs. In early 2022, the European Commission took a stronger stance against the current industrial model, arguing that the new paradigm of Industry 5.0 is necessary to address the climate crisis [72]. The proper use of technologies like additive manufacturing or artificial intelligence can play a significant role in optimizing resources and minimizing waste.

4.3. Resilience in Industry 5.0

The aim of Industry 5.0 also focuses on improving production systems to address disruptions and adapt quickly. The aim is to ensure its role as a sustainable driver [58]. It seeks to ensure adaptable and flexible processes, especially when they involve basic human needs such as safety or healthcare [7]. In the current global context, industry can no longer rely solely on technological development driven by economic gains [6]. To achieve a thriving industry, it is essential for systems to evolve toward an approach that considers all aspects of a sociotechnical system [38]. This implies effectively integrating technologies into collaborative and sustainable work environments. The concept of Industry 5.0 supported by the European Commission is not just about economic development but rather about it being a product of a social and environmental system, promoted by a resilient industry in the long term [61].

4.4. Strategic Values in Industry 5.0: Guiding Technological Transformation

The new industrial paradigm revolves around the idea that technologies must be designed to support a set of strategic values. The aim is for technological transformation to be designed in harmony with the needs of society [7]. To ensure that fundamental values are respected, it is necessary to consider them at the early stages of each process [73]. These values can be categorized under the three major focuses of Industry 5.0 (human-centricity, sustainability, and resilience), and, in turn, can be studied at three levels of analysis (macro, meso, and micro). Figure 3 provides a classification of a series of values that can be respected during the technological development process of Industry 5.0 [74]. In the social focus (blue), there are values related to safety and occupational health [75]. In the sustainable focus (green), values such as altruism, diversity, and respect for nature are highlighted [76]. Finally, in the resilient focus (orange), the values are designed to guide decisions in adverse situations [77].

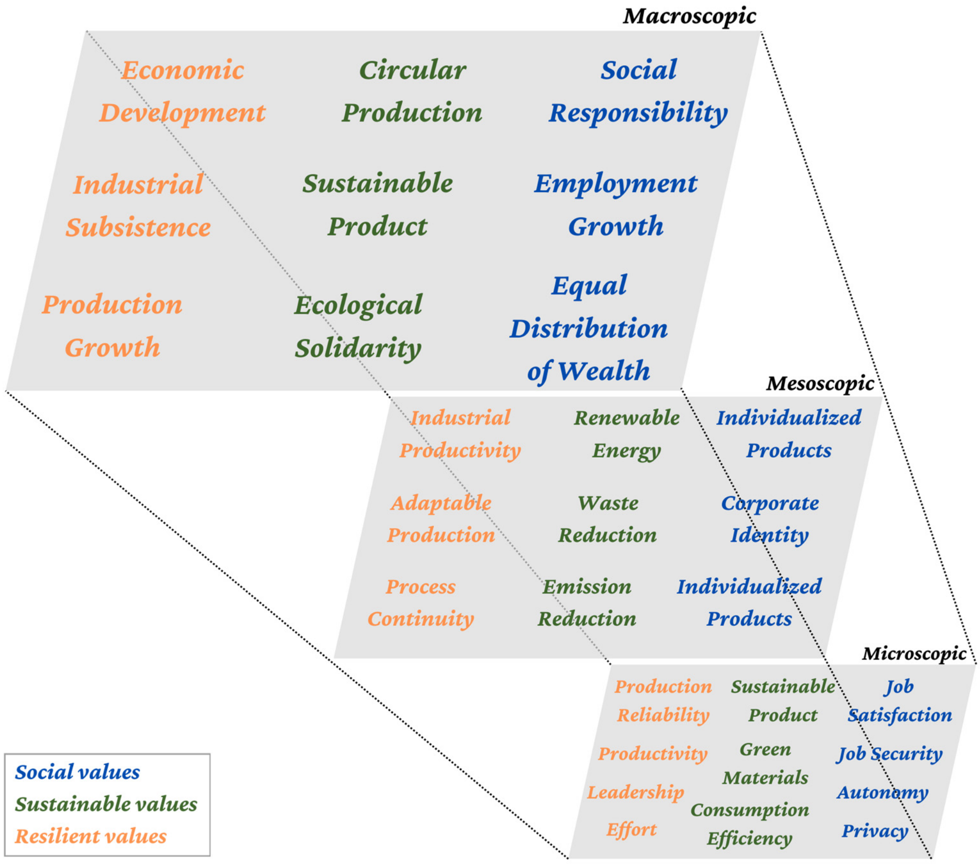

Figure 3. Classification of values in Industry 5.0.

Values are the starting point for the shift in the industrial paradigm. However, research arises on how to achieve that transformation based on these values. The design principles that make it possible for the key components of Industry 5.0 to take place are called techno-functional principles [74]. Through an advanced review of the current literature on this topic, it has been possible to identify eight technofunctional principles: Decentralization, based on data transparency and interconnection between objects and people; vertical integration, based on creating networks and integrating processes; horizontal integration, based on the seamless exchange of production data across the entire manufacturing network; interoperability, based on the ability of industrial systems to communicate reliably throughout their value chains; modularity, based on the ability to break down a value chain into modules; real-time capability, based on the real-time collection and analysis of production data; technical assistance, based on adapting technology to human skills; and virtualization, based on creating a digital replica of an industrial system.

4.5. Enabling Technologies of Industry 5.0

The enabling technologies of Industry 5.0 consist of digital technologies integrated with cognitive abilities and innovation. Although a group of emerging technologies is identified in the context of Industry 5.0 [78], these new technologies are being supported by facilitating technologies developed under the paradigm of Industry 4.0. Enabling technologies can be subcategorized into facilitating technologies and groups of emerging technologies [74]. Facilitating technologies like cobots or big data make Industry 5.0 an advanced production model centered on human–machine interaction [69]. Emerging technologies represent disruptive innovations that build on facilitating technologies to drive more efficient value creation methods [79]. Table 3 lists nine emerging technologies that support the aims of Industry 5.0 [80].

Table 3. Enabling technologies of Industry 5.0.

Technology	Description
Cognitive Artificial Intelligence (CAI)	This technology is presented as an essential component in Industry 5.0 as it will enable better decision-making and generate more sustainable products [69].
Extended reality (XR)	XR technologies are beneficial for various stakeholders in the context of Industry 5.0, and they are expected to continue developing in the current market [43].
Human interaction and recognition technologies (HIRT)	These technologies aim to seamlessly connect and integrate humans with machinery [81]. The result is safer and more beneficial physical and cognitive tasks.
Cognitive Cyber–Physical Systems (C-CCP)	C-CCP acknowledge the role of human cognition within CPS, resulting in a smoother human–machine interaction in all operations [82].
Industrial Smart Wearable (ISW)	Currently, there is a wide range of ISWs offering various functionalities to workers. ISWs enable to operate more safely, quickly, and productively [83].
Intelligent Energy Management Systems (IEMS)	IEMS promote energy efficiency through the control and monitoring of systems, improving the technical efficiency of energy production and system reliability [84].
Intelligent or Adaptive Robots	These are defined as highly productive robots capable of adapting to complex environments and novel situations in the execution of complex tasks [85].
Dynamic Simulation and Digital Twin (DSDT)	DSDT technologies combine physical and virtual worlds. The digital representation of products allows for the detection of design inefficiencies and performance issues [86].
Smart Product Lifecycle Management (SPLM)	SPLM systems create digital models of processes, products, or services to facilitate process integration and the creation of smart products [87].

5. Design of Manufacturing Systems from Sociotechnical Systems for the Incorporation of Enabling Technologies of Industry 5.0

The proposed design model is derived from the research carried out and is applied at the industrial production line level. The model allows for the integration of sociotechnical theory into each stage of manufacturing, considering the objectives of Industry 5.0 [88]. From the top, the values of Industry 5.0 are integrated, serving as the starting point for any design problem within the new industrial paradigm. These values are integrated following a set of design principles. These technofunctional principles will guide the digital transformation process [74]. However, they will require different design tools to put the design processes into practice [43]. Once the technology is designed using sociotechnical theory and target values, it can be employed in a multitude of manufacturing activities that involve human interaction [89].

The proposed design model contributes to reducing the metabolic rift evident in contemporary sociotechnical systems. This is underpinned by the paradigm shift introduced by Industry 5.0. By foregrounding human, sustainable, and resilient values in the design and implementation of manufacturing systems, a holistic perspective is adopted to mitigate the growing gap that has emerged between natural capital and social capital in the industrial context [79]. Industry 5.0 becomes a catalyst for change, fostering collaboration and coevolution between humans and technology. The proposed design model aims to transform the industry into an engine of sustainable and equitable progress. By embracing a comprehensive vision that prioritizes human and environmental values, the groundwork is laid for a new industrial era where economic prosperity is balanced with the preservation of nature and the well-being of society [80].

The research carried out shows the possibility of using various tools that enable the design of technology while considering ethical objectives. Sustainable design [90], inclusive design [91], and universal design [92] are widely adopted methodologies in this field. However, the tool that seems to be most used in the design of technologies that meet the values of the new industrial paradigm is Value-Sensitive Design (VSD) [93]. This methodology is prevalent in the human–machine interaction domain due to its robustness, applicability, and inclusion of all stakeholders [94]. VSD establishes the values that must be respected during the design process, analyzes the degree of compliance that technologies have with the established values, and, finally, involves all stakeholders and establishes continuous monitoring of the process.

5.1. Integration of Sociotechnical Theory

Sociotechnical theory must be considered in every activity that makes up the manufacturing process. It should be integrated by organizational management, where the mission, vision, and values of a company are considered (macro) [95], all the way to technological applications involving human interaction (micro). The first step in integration is the analysis of sociotechnical interactions. This involves studying how technologies affect the workflow and influence the social dynamics of a factory [96]. Along with this analysis, factors such as technology acceptance and worker training must be considered [97]. Figure 4 represents the process of integrating sociotechnical theory, considering social, technological, infrastructural, and organizational aspects. The model considers it necessary to implement effective change management strategies to ensure that workers remain skilled [98]. Along with these strategies, a process of continuous monitoring and evaluation of the system is established. Based on the results obtained, sociotechnical integration is adjusted and optimized [99].

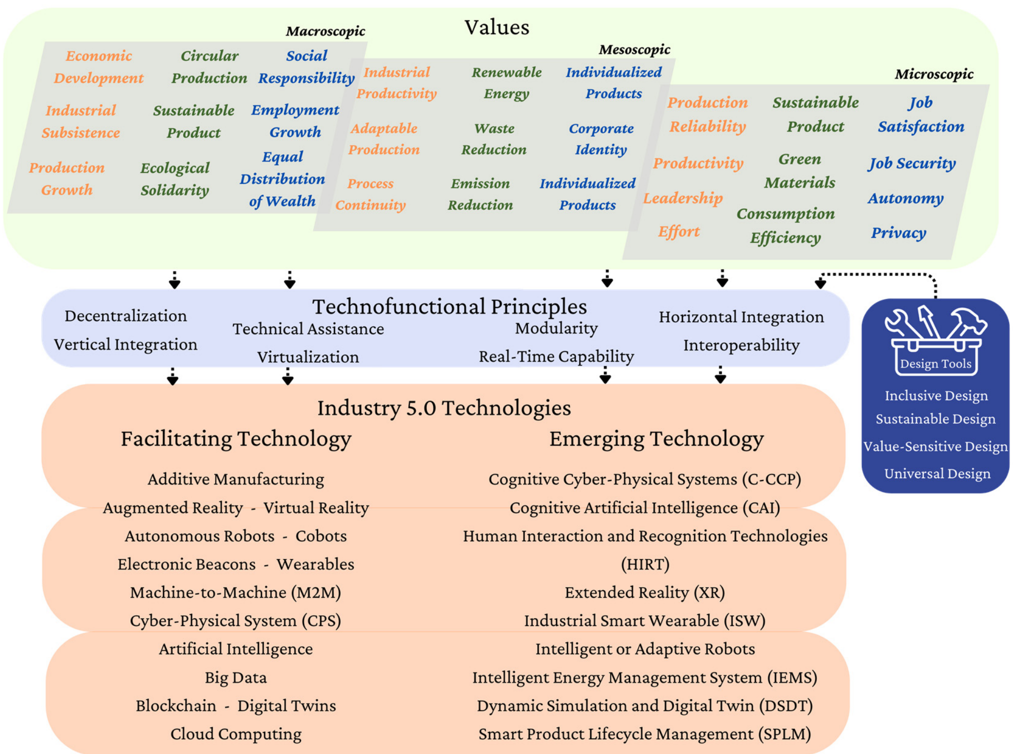

Figure 4. Design of Industry 5.0 technologies: values, technofunctional principles, and design tools.

5.2. Contribution of Enabling Technologies to Social/Smart Manufacturing

Data analysis identified 19 key enabling technologies. These technologies are the product of the technological drive of Industry 4.0 [100]. However, reconsidering their design under the values of Industry 5.0 and following sociotechnical theory, they facilitate the new industrial paradigm [81]. Most of these technologies can be applied at all stages of any manufacturing process. However, they are more relevant at those stages where they significantly contribute to increased efficiency, quality, and human satisfaction [101]. Table 4 provides a classification of this technologies under eight stages of a generic manufacturing process. The intermediate cells represent the association between technology and activity. Empty cells reflect that no relevant reference literature was found for that relationship.

Table 4. Allocation of enabling technologies at different stages of an industrial process.

Technology	Engineering	Training	Machine Operation	Assembly	Quality Control	Maintenance	Materials Movement
Additive Manufacturing				✓		✓	
Augmented Reality	✓	✓	✓	✓	✓	✓	
Virtual Reality	✓	✓	✓	✓	✓	✓	
Autonomous Robots				✓	✓		✓
Cobots	✓		✓	✓		✓	✓
Electronic Beacons				✓			✓
Wearables		✓	✓	✓		✓	✓
Middleware				✓			✓
Radiofrequency Identification		✓	✓			✓	
Machine-to-machine (M2M)			✓		✓		
Cyber-Physical System (CPS)	✓	✓	✓		✓		
Artificial Intelligence		✓	✓			✓	
Big Data	✓	✓		✓			✓
Blockchain	✓						
Digital Twins			✓	✓		✓	
Cloud Computing	✓			✓			✓
Cybersecurity	✓						
Internet of Things (IoT)	✓		✓	✓		✓	
Edge Computing		✓		✓	✓		

Activities that involve machine operations can make use of a wide range of technologies. This includes the use of collaborative robots to perform more tedious tasks [102], the implementation of digital models to streamline operations and avoid delays in decision-making [103], and the use of wearables to track work activity [104]. In material movement, the use of electronic beacons allows for real-time data collection [104]. These data, along with technologies like cloud computing and big data, can be used to improve working conditions [105]. In the quality control area, augmented reality is used to eliminate the physical elements that limit the mobility of the hands of workers [106], and M2M enables communication between inspection devices and control systems, allowing for automated, efficient, and safe inspection [107]. Assembly activities make use of technologies such as virtual reality to intuitively guide the assembly process [108]. Additionally, the use of exoskeletons to enhance operators' capabilities and improve efficiency at this stage is notable [109]. Engineering activities utilize augmented reality and virtual reality to reconfigure products before their manufacturing [110]. These, along with the Internet of Things (IoT), contribute to the continuous improvement of processes [111]. In maintenance, technologies like augmented reality, combined with voice assistants, assist specialists [112]. When these technologies are combined with the use of digital twins, multiple variables can be evaluated simultaneously [113]. Wearable devices, voice assistants, and virtual and augmented reality technologies are used in training activities to enhance the quality of worker training [114]. This allows for simulating reality without exposing workers to any risks [115].

As Figure 5 shows, the integration of Industry 5.0 values with sociotechnical theory prioritizes social and sustainable factors over the importance of technology in the efficiency of an organization. This approach paves a new path toward an industrial future where economic prosperity is not in conflict with the preservation of the environment and the well-being of society [95]. Industry 5.0 shifts the paradigm of the current industrial model. Enabling technologies not only drive efficiency and quality but also enhance worker satisfaction, contributing to a healthier and more productive work environment. This holistic and multidimensional approach promises to revolutionize the way industrial production is conceived [116].

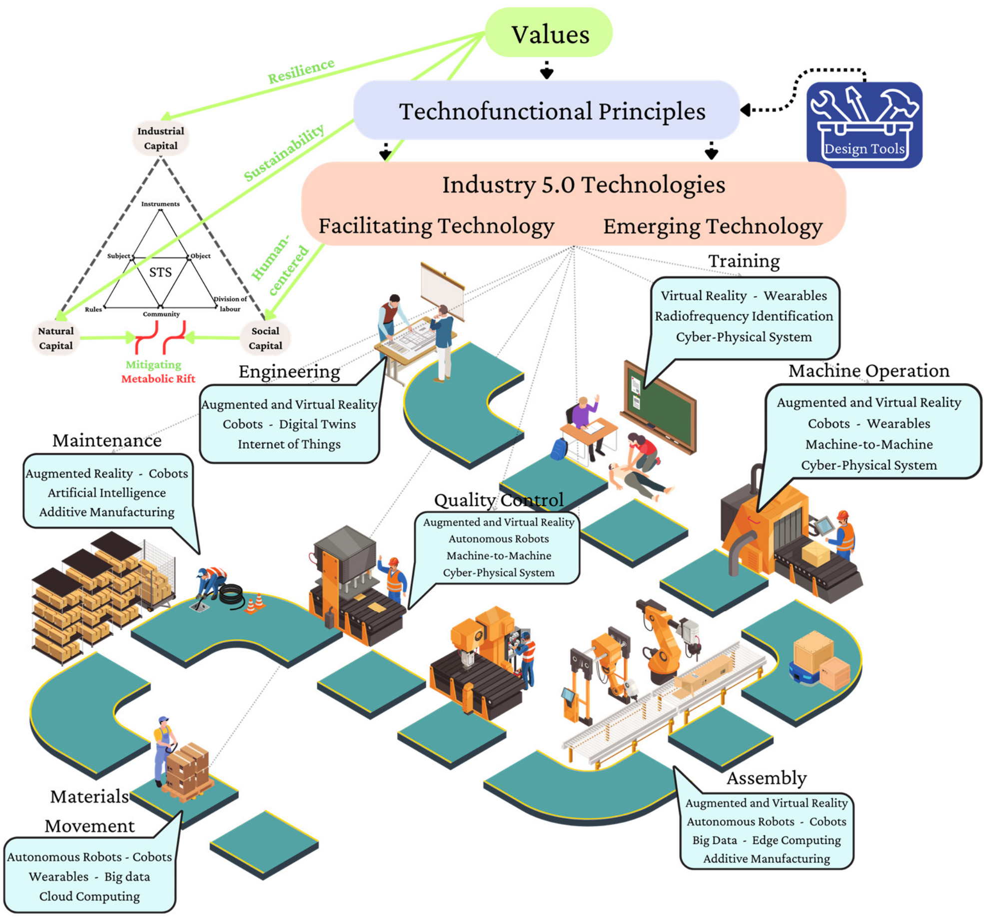

Figure 5. Identification of enabling technologies by workstation in the proposed design model.

6. Conclusions

The study of some sociotechnical transitions reflects that they have taken long periods of time to develop. However, it has been observed that recently, transitions are happening more quickly [117]. This phenomenon opens a debate about whether sociotechnical transitions can occur faster if consciously governed, whereas, historically, they were emergent processes driven by the market. Public policies play a key role in influencing the speed of sociotechnical advancements in this manner [118].

The literature reflects that Industry 4.0 has successfully achieved the expected levels of productivity. However, it does not prioritize social and environmental sustainability, despite mildly promoting some values. Industry 5.0 promotes the human element via workforce reskilling, adapting technological development to the needs of workers, and improving the safety, health, and ergonomics of work environments. Additionally, it involves managing the impact of natural crises caused by humans themselves [119].

This study has identified key enabling technologies for various stages of the industrial process within the context of Industry 5.0. It contributes to a robust theoretical framework for designing sociotechnical systems that integrate these technologies based on the core values of Industry 5.0. Emphasizing a human-centric approach, the framework ensures technology adapts to human needs, promoting safe and ethical workplaces. This research offers valuable guidance for the ethical and sustainable implementation of enabling technologies in Industry 5.0, aligning manufacturing systems with its fundamental values.

The main limitation of this study is due to the immature state of the concept of Industry 5.0. This means that the model is developed at a metalevel, considering the integration of sociotechnical theory with the principles of Industry 5.0 at a theoretical level. This study will expand knowledge about the design of integration frameworks in Industry 5.0. However, future studies should explore case studies to design sociotechnical systems in the context of the new industrial paradigm. The nascent state of Industry 5.0 leaves many questions unanswered. If human-centered technological advancements are to be driven by governments, what legislative framework should be used? How can they be promoted uniformly worldwide to ensure human centricity is balanced? What support programs should be created? Future research is encouraged to address these questions to ensure a development in line with the objectives and values initially proposed by Industry 5.0.

This article presents a theoretical model for the design of sustainable manufacturing systems, based on the assessment of enabling technologies in line with the values of Industry 5.0 and the pillars of sustainability. However, it is crucial to recognize that the proposed model has not yet been verified or validated in practical environments. As a direction for future research, the implementation of pilot case studies in real manufacturing settings is suggested. These studies should address the implementation of the model in specific manufacturing systems, evaluating its effectiveness in terms of enhancing sustainability and alignment with the values of Industry 5.0. Additionally, a quantitative measurement of the sustainability indicators predefined in the model could be carried out, allowing for an empirical validation of its ability to meet sustainability objectives. This verification and validation phase will provide a solid foundation for the practical application of the model in the industry and the continuous refinement of sustainable manufacturing system design strategies.

Author Contributions: Conceptualization, A.A.-G., A.M.M.-G. and J.R.L.-R.; methodology, A.A.-G. and A.M.M.-G.; investigation, A.A.-G. and A.M.M.-G.; writing—original draft preparation, A.A.-G.; writing—review and editing, 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.

Data Availability Statement: Not applicable.

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

References

1. Gabriel, W.; Madelrieux, S.; Lescoat, P. A review of socio-economic metabolism representations and their links to action: Cases in agri-food studies. *Ecol. Econ.* **2020**, *178*, 106765. [CrossRef]
2. Afshan, S.; Ozturk, I.; Yaqoob, T. Facilitating renewable energy transition, ecological innovations and stringent environmental policies to improve ecological sustainability: Evidence from MM-QR method. *Renew. Energy* **2022**, *196*, 151–160. [CrossRef]
3. Sopiana, Y.; Ade, M.; Harahap, K. Sustainable Urban Planning: A Holistic Approach to Balancing Environmental Conservation, Economic Development, and Social Well-being. *West. Sci. Interdiscip. Stud.* **2023**, *1*, 43–53.
4. Emery, F.E.; Trist, E.L. Socio-technical systems. *Manag. Sci. Models Tech.* **1960**, *2*, 83–97.
5. Fraboni, F.; Brendel, H.; Pietrantoni, L. Evaluating Organizational Guidelines for Enhancing Psychological Well-Being, Safety, and Performance in Technology Integration. *Sustainability* **2023**, *15*, 8113. [CrossRef]
6. Grabowska, S.; Saniuk, S.; Gajdzik, B. Industry 5.0: Improving humanization and sustainability of Industry 4.0. *Scientometrics* **2022**, *127*, 3117–3144. [CrossRef]
7. Breque, M.; De Nul, L.; Petridis, A. *Industry 5.0: Towards a Sustainable, Human-Centric and Resilient European Industry*; European Commission, Directorate-General for Research and Innovation: Brussels, Belgium, 2021.
8. Foster, J.B. Marx's Theory of Metabolic Rift: Classical Foundations for Environmental Sociology. *Am. J. Sociol.* **1999**, *105*, 366–405. [CrossRef]
9. Pauliuk, S.; Müller, D.B. The role of in-use stocks in the social metabolism and in climate change mitigation. *Glob. Environ. Change* **2014**, *24*, 132–142. [CrossRef]
10. Haberl, H.; Wiedenhofer, D.; Pauliuk, S.; Krausmann, F.; Müller, D.B.; Fischer-Kowalski, M. Contributions of sociometabolic research to sustainability science. *Nat. Sustain.* **2019**, *2*, 173–184. [CrossRef]
11. Bleischwitz, R.; Spataru, C.; VanDeveer, S.D.; Obersteiner, M.; van der Voet, E.; Johnson, C.; Van Vuuren, D.P. Resource nexus perspectives towards the United Nations Sustainable Development Goals. *Nat. Sustain.* **2018**, *1*, 737–743. [CrossRef]
12. Hauschild, M.Z.; Kara, S.; Røpke, I. Absolute sustainability: Challenges to life cycle engineering. *CIRP Ann.* **2020**, *69*, 533–553. [CrossRef]
13. Geels, F.W. Technological transitions as evolutionary reconfiguration processes: A multi-level perspective and a case-study. *Res. Policy* **2002**, *31*, 1257–1274. [CrossRef]
14. Chapin, F.S., III; Power, M.E.; Pickett, S.T.; Freitag, A.; Reynolds, J.A.; Jackson, R.B.; Lodge, D.M.; Duke, C.; Collins, S.L.; Bartuska, A.; et al. Earth Stewardship: Science for action to sustain the human-earth system. *Ecosphere* **2011**, *2*, 1–20. [CrossRef]
15. Bjørn, A.; Margni, M.; Roy, P.O.; Bulle, C.; Hauschild, M.Z. A proposal to measure absolute environmental sustainability in life cycle assessment. *Ecol. Indic.* **2016**, *63*, 1–13. [CrossRef]
16. Stewart, R.; Cynthia, H.; Thomas, B.; Walter, R. Complexity Science and Organization Studies. In *The SAGE Handbook of Organization Studies*; Sage Publications Ltd.: Newcastle on Tyne, UK, 2006; pp. 1–895. [CrossRef]
17. Trist, E.L.; Bamforth, K.W. Some social and psychological consequences of the longwall method of coal-getting: An examination of the psychological situation and defences of a work group in relation to the social structure and technological content of the work system. *Hum. Relat.* **1951**, *4*, 3–38. [CrossRef]
18. Mumford, E. The story of socio-technical design: Reflections on its successes, failures and potential. *Inf. Syst. J.* **2006**, *16*, 317–342. [CrossRef]
19. Ngowi, L. Socio Technical Systems: Transforming Theory into Practice. *Complex. Syst. Optim.* **2018**, *12*, 310–316. [CrossRef]
20. Badham, R.; Clegg, C.; Wall, T. Socio-technical theory. In *Handbook of Ergonomics*; John Wiley: New York, NY, USA, 2000.
21. Trist, E.; Murray, H. *The Social Engagement of Social Science: The Socio-Technical Perspective*; University of Pennsylvania Press: Philadelphia, PA, USA, 1993; Volume 2.
22. Davis, L.E.; Taylor, J.C. *The Design of Jobs*; Penguin Books: Harmondsworth, UK, 1972.
23. Herbst, P.G. Designing with minimal critical specifications. In *Socio-Technical Design: Strategies in Multidisciplinary Research*; Tavistock Publications: London, UK, 1974.
24. Cherns, A. Principles of socio-technical design. *Hum. Relat.* **1976**, *2*, 783–792. [CrossRef]
25. Toomela, A. Activity theory is a dead end for cultural-historical psychology. *Cult. Psychol.* **2000**, *6*, 353–364. [CrossRef]
26. Tran, T.; Valecha, R.; Rao, H.R. Machine and human roles for mitigation of misinformation harms during crises: An activity theory conceptualization and validation. *Int. J. Inf. Manag.* **2023**, *70*, 102627. [CrossRef]
27. Lu, Q.; Chen, L.; Lee, S.; Zhao, X. Activity theory-based analysis of BIM implementation in building O&M and first response. *Autom. Constr.* **2018**, *85*, 317–332. [CrossRef]
28. Kwong, Y.C.; Churchill, D. Applying the Activity Theory framework to analyse the use of ePortfolios in an International Baccalaureate Middle Years Programme Sciences classroom: A longitudinal multiple-case study. *Comput. Educ.* **2023**, *200*, 104792. [CrossRef]
29. Checkland, P. Systems thinking. In *Rethinking Management Information Systems*; Oxford University Press: Oxford, UK, 1999; pp. 45–56.
30. Sommerville, I.; Dewsbury, G. Dependable domestic systems design: A socio-technical approach. *Interact. Comput.* **2007**, *19*, 438–456. [CrossRef]
31. Waterson, P.E.; Gray, M.T.O.; Clegg, C.W. A Sociotechnical Method for Designing Work Systems. *Sage J.* **2002**, *44*, 376–391. [CrossRef]

32. Martin, D.; Sommerville, I. Patterns of cooperative interaction: Linking ethnomethodology and design. *ACM Trans. Comput. Hum. Interact.* **2004**, *11*, 59–89. [CrossRef]
33. Beyer, H.; Holtzblatt, K. Contextual design. *Interactions* **1999**, *6*, 32–42. [CrossRef]
34. Majchrzak, A.; Borys, B. Generating testable socio-technical systems theory. *J. Eng. Technol. Manag.* **2001**, *18*, 219–240. [CrossRef]
35. Maguire, M. Methods to support human-centred design. *Int. J. Hum. Comput. Stud.* **2001**, *55*, 587–634. [CrossRef]
36. Marx, K. *Capital*; A Critique of Political Economy; Foreign Languages Publishing House: Pyongyang, Republic of Korea, 2015; Volume 1.
37. Ahlborg, H.; Ruiz-Mercado, I.; Molander, S.; Masera, O. Bringing Technology into Social-Ecological Systems Research—Motivations for a Socio-Technical-Ecological Systems Approach. *Sustainability* **2019**, *11*, 2009. [CrossRef]
38. Beier, G.; Ullrich, A.; Niehoff, S.; Reißig, M.; Habich, M. Industry 4.0: How it is defined from a sociotechnical perspective and how much sustainability it includes—A literature review. *J. Clean. Prod.* **2020**, *259*, 120856. [CrossRef]
39. Leuvennink, J.; Kruger, K.; Basson, A. Architectures for human worker integration in holonic manufacturing systems. *Stud. Comput. Intell.* **2019**, *803*, 133–144. [CrossRef]
40. Fayomi, S.I.; Akande, I.G.; Esse, U.C.; Oladipupo, S. Examining the roles and challenges of human capital influence on 4th industrial revolution. *AIP Conf. Proc.* **2020**, *2307*, 20039. [CrossRef]
41. Pacaux-Lemoine, P.; Trentesaux, D.; Rey, G.Z.; Millot, P. Designing intelligent manufacturing systems through Human-Machine Cooperation principles: A human-centered approach. *Comput. Ind. Eng.* **2017**, *111*, 581–595. [CrossRef]
42. Wang, S.; Wan, J.; Li, D.; Zhang, C. Implementing Smart Factory of Industrie 4.0: An Outlook. *Int. J. Distrib. Sens. Netw.* **2016**, *12*, 3159805. [CrossRef]
43. Longo, F.; Padovano, A.; Umbrello, S. Value-Oriented and Ethical Technology Engineering in Industry 5.0: A Human-Centric Perspective for the Design of the Factory of the Future. *Appl. Sci.* **2020**, *10*, 4182. [CrossRef]
44. Gazzaneo, L.; Padovano, A.; Umbrello, S. Designing smart operator 4.0 for human values: A value sensitive design approach. *Procedia Manuf.* **2020**, *42*, 219–226. [CrossRef]
45. Brettel, M.; Friederichsen, N.; Keller, M.; Rosenberg, M. How virtualization, decentralization and network building change the manufacturing landscape: An industry 4.0 perspective. *Int. J. Inf. Commun. Eng.* **2014**, *8*, 37–44.
46. Ras, E.; Wild, F.; Stahl, C.; Baudet, A. Bridging the skills gap of workers in industry 4.0 by human performance augmentation tools—Challenges and roadmap. In Proceedings of the 10th International Conference on PErvasive Technologies Related to Assistive Environments, Island of Rhodes, Greece, 21–23 June 2017; Part F128530, pp. 428–432. [CrossRef]
47. Schumacher, A.; Erol, S.; Sihn, W. A Maturity Model for Assessing Industry 4.0 Readiness and Maturity of Manufacturing Enterprises. *Procedia CIRP* **2016**, *52*, 161–166. [CrossRef]
48. Davis, M.C.; Challenger, R.; Jayewardene, D.N.W.; Clegg, C.W. Advancing socio-technical systems thinking: A call for bravery. *Appl. Ergon.* **2014**, *45*, 171–180. [CrossRef]
49. Sony, M.; Naik, S. Industry 4.0 integration with socio-technical systems theory: A systematic review and proposed theoretical model. *Technol. Soc.* **2020**, *61*, 101248. [CrossRef]
50. Leavitt, H. Applying organizational change in industry: Structural, technological, and humanistic approaches. In *Handbook of Organizations*; Routledge: London, UK, 1965.
51. Challenger, R.; Clegg, W. Crowd disasters: A socio-technical systems perspective. *Contemp. Soc. Sci.* **2011**, *6*, 343–360. [CrossRef]
52. Munro, R.; Cairney, P. A systematic review of energy systems: The role of policymaking in sustainable transitions. *Renew. Sustain. Energy Rev.* **2020**, *119*, 109598. [CrossRef]
53. Hägerstrand, T. On socio-technical ecology and the study of innovations. *Ethnol. Eur.* **1974**, *7*, 17–34.
54. Hoppmann, J.; Huenteler, J.; Girod, B. Compulsive policy-making—The evolution of the German feed-in tariff system for solar photovoltaic power. *Res. Policy* **2014**, *43*, 1422–1441. [CrossRef]
55. Lauber, V.; Jacobsson, S. The politics and economics of constructing, contesting and restricting socio-political space for renewables—The German Renewable Energy Act. *Environ. Innov. Soc. Transit.* **2016**, *18*, 147–163. [CrossRef]
56. Zhang, H. Blockchain facilitates a resilient supply chain in steel manufacturing under COVID-19. In Proceedings of the 22nd European Conference on Knowledge Management, ECKM 2021, Coventry, UK, 2–3 September 2021; pp. 964–972.
57. Rogers, P.; Bohland, J.J.; Lawrence, J. Resilience and values: Global perspectives on the values and worldviews underpinning the resilience concept. *Polit. Geogr.* **2020**, *83*, 102280. [CrossRef]
58. Ivanov, D. The Industry 5.0 framework: Viability-based integration of the resilience, sustainability, and human-centricity perspectives. *Int. J. Prod. Res.* **2022**, *61*, 1683–1695. [CrossRef]
59. Lee, J.; Bagheri, B.; Kao, H.A. A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems. *Manuf. Lett.* **2015**, *3*, 18–23. [CrossRef]
60. Sparrow, D.E.; Kruger, K.; Basson, A.H. Human Digital Twin for integrating human workers in Industry 4.0. In Proceedings of the International Conference on Competitive Manufacturing, Stellenbosch, South Africa, 31 January–2 February 2019; pp. 1–6.
61. Müller, J. *Enabling Technologies for Industry 5.0: Results of a Workshop with Europe's Technology Leaders*; European Commission, Directorate-General for Research and Innovation: Brussels, Belgium, 2020.
62. Garrido, A.; Gómez, A.M.; Ruiz, J.R.L. Industry 5.0 Values. A bibliometric analysis of the new industrial paradigm from the social approach. *DYNA September* **2023**, *98*, 531–536. [CrossRef]

63. Leong, Y.K.; Tan, J.H.; Chew, K.W.; Show, P.L. Significance of Industry 5.0. In *The Prospect of Industry 5.0 in Biomanufacturing*; CRC Press: Boca Raton, FL, USA, 2021; pp. 95–114. [CrossRef]
64. Mourtzis, D.; Angelopoulos, J.; Panopoulos, N. A Literature Review of the Challenges and Opportunities of the Transition from Industry 4.0 to Society 5.0. *Energies* **2022**, *15*, 6276. [CrossRef]
65. Romero, D.; Stahre, J. Towards the Resilient Operator 5.0: The Future of Work in Smart Resilient Manufacturing Systems. *Procedia CIRP* **2021**, *104*, 1089–1094. [CrossRef]
66. Ordieres-Meré, J.; Gutierrez, M.; Villalba-Díez, J. Toward the industry 5.0 paradigm: Increasing value creation through the robust integration of humans and machines. *Comput. Ind.* **2023**, *150*, 103947. [CrossRef]
67. Javaid, M.; Haleem, A.; Singh, R.P.; Haq, M.I.U.; Raina, A.; Suman, R. Industry 5.0: Potential applications in COVID-19. *J. Ind. Integr. Manag.* **2020**, *5*, 507–530. [CrossRef]
68. Gorecky, D.; Schmitt, M.; Loskyll, M.; Zühlke, D. Human-machine-interaction in the industry 4.0 era. In Proceedings of the 2014 12th IEEE International Conference on Industrial Informatics, INDIN 2014, Porto Alegre, Brazil, 27–30 July 2014; pp. 289–294. [CrossRef]
69. Maddikunta, P.K.R.; Pham, Q.V.; Prabadevi, B.; Deepa, N.; Dev, K.; Gadekallu, T.R.; Ruby, R.; Liyanage, M. Industry 5.0: A survey on enabling technologies and potential applications. *J. Ind. Inf. Integr.* **2022**, *26*, 100257. [CrossRef]
70. Evangelopoulos, N.; Zhang, X.; Prybutok, V.R. Latent semantic analysis: Five methodological recommendations. *Eur. J. Inf. Syst.* **2012**, *21*, 70–86. [CrossRef]
71. Coronado, E.; Kiyokawa, T.; Ricardez, G.A.G.; Ramirez-Alpizar, I.G.; Venture, G.; Yamanobe, N. Evaluating quality in human-robot interaction: A systematic search and classification of performance and human-centered factors, measures and metrics towards an industry 5.0. *J. Manuf. Syst.* **2022**, *63*, 392–410. [CrossRef]
72. Directorate-General for Research and Innovation. *Industry 5.0, a Transformative Vision for Europe: Governing Systemic Transformations towards a Sustainable Industry*; Directorate-General for Research and Innovation: Brussels, Belgium, 2022.
73. Chin, T.S. Influence of emotional intelligence on the workforce for industry 5.0. *J. Hum. Resour. Manag. Res.* **2021**, *2021*, 882278. [CrossRef]
74. 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]
75. Friedman, P.H.K., Jr. Human values, ethics, and design. In *The Human-Computer Interaction Handbook*; CRC Press: Boca Raton, FL, USA, 2007; pp. 1267–1292. [CrossRef]
76. Dietz, T.; Fitzgerald, A.; Shwom, R. Environmental values. *Annu. Rev. Environ. Resour.* **2005**, *30*, 335–372. [CrossRef]
77. Zebrowski, C. *The Value of Resilience: Securing Life in the Twenty-First Century*; Routledge: London, UK, 2015; pp. 1–160.
78. Choi, M.; Kumar, S.; Yue, X.; Chan, H.L. Disruptive Technologies and Operations Management in the Industry 4.0 Era and Beyond. *Prod. Oper. Manag.* **2022**, *31*, 9–31. [CrossRef]
79. 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]
80. Sindhwani, R.; Afridi, S.; Kumar, A.; Banaitis, A.; Luthra, S.; Singh, P.L. Can industry 5.0 revolutionize the wave of resilience and social value creation? A multi-criteria framework to analyze enablers. *Technol. Soc.* **2022**, *68*, 101887. [CrossRef]
81. Nahavandi, S. Industry 5.0—A Human-Centric Solution. *Sustainability* **2019**, *11*, 4371. [CrossRef]
82. Saadati, Z.; Barenji, R.V. *Toward Industry 5.0: Cognitive Cyber-Physical System*; MIT Pres: Cambridge, MA, USA, 2023; pp. 257–268. [CrossRef]
83. Jan, M.A.; Khan, F.; Khan, R.; Mastorakis, S.; Menon, V.G.; Alazab, M.; Watters, P. Lightweight Mutual Authentication and Privacy-Preservation Scheme for Intelligent Wearable Devices in Industrial-CPS. *IEEE Trans. Ind. Inf.* **2021**, *17*, 5829–5839. [CrossRef] [PubMed]
84. Kermani, M.; Adelmanesh, B.; Shirdare, E.; Sima, C.A.; Carnì, D.L.; Martirano, L. Intelligent energy management based on SCADA system in a real Microgrid for smart building applications. *Renew. Energy* **2021**, *171*, 1115–1127. [CrossRef]
85. Schneider, S.; Kummert, F. Comparing Robot and Human guided Personalization: Adaptive Exercise Robots are Perceived as more Competent and Trustworthy. *Int. J. Soc. Robot.* **2021**, *13*, 169–185. [CrossRef]
86. Kaewunruen, S.; Lian, Q. Digital twin aided sustainability-based lifecycle management for railway turnout systems. *J. Clean. Prod.* **2019**, *228*, 1537–1551. [CrossRef]
87. Liu, Y.; Zhang, Y.; Ren, S.; Yang, M.; Wang, Y.; Huisingh, D. How can smart technologies contribute to sustainable product lifecycle management? *J. Clean. Prod.* **2020**, *249*, 119423. [CrossRef]
88. Majerník, M.; Daneshjo, N.; Malega, P.; Drábik, P.; Barilová, B. Sustainable Development of the Intelligent Industry from Industry 4.0 to Industry 5.0. *Adv. Sci. Technol. Res. J.* **2022**, *16*, 12–18. [CrossRef]
89. de Assis, J.; 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]
90. Bhamra, S.; Lofthouse, V. Design for sustainability: A practical approach. In *Design for Sustainability: A Practical Approach*; CRC Press: New York, NY, USA, 2016; pp. 1–184. [CrossRef]

91. Newell, F.; Gregor, P.; Morgan, M.; Pullin, G.; Macaulay, C. User-Sensitive Inclusive Design. *Univ. Access Inf. Soc.* **2011**, *10*, 235–243. [CrossRef]
92. Ruzic, L.; Lee, S.T.; Liu, Y.E.; Sanford, J.A. Development of universal design mobile interface guidelines (UDMIG) for aging population. *Lect. Notes Comput. Sci.* **2016**, *9737*, 98–108. [CrossRef]
93. Umbrello, S.; De Bellis, A.F. A Value-Sensitive Design Approach to Intelligent Agents. *Artif. Intell. Saf. Secur.* **2018**, *2018*, 395–409. [CrossRef]
94. Friedman, B. *Value Sensitive Design: Shaping Technology with Moral Imagination*; MIT Press: Cambridge, MA, USA, 2019. Available online: https://mitpress.mit.edu/9780262039536/value-sensitive-design/ (accessed on 30 October 2022).
95. Banholzer, V.M. From Industry 4.0 to Industry 5.0—An Overview of European Union Enterprises. *Technol. Soc. Innov. Asp. Syst. Transform.* **2022**, *3*, 221–231. [CrossRef]
96. John, N.; Wesseling, J.H.; Worrell, E.; Hekkert, M. How key-enabling technologies' regimes influence sociotechnical transitions: The impact of artificial intelligence on decarbonization in the steel industry. *J. Clean. Prod.* **2022**, *370*, 133624. [CrossRef]
97. Zhang, M.; Shu, L.; Luo, X.; Yuan, M.; Zheng, X. Virtual reality technology in construction safety training: Extended technology acceptance model. *Autom. Constr.* **2022**, *135*, 104113. [CrossRef]
98. Nguyen, M.; Rundle-Thiele, S.; Malik, A.; Budhwar, P. Impact of technology-based knowledge sharing on employee outcomes: Moderation effects of training, support and leadership. *J. Knowl. Manag.* 2023, *ahead-of-print*. [CrossRef]
99. Gallego-García, S.; Groten, M.; Halstrick, J. Integration of Improvement Strategies and Industry 4.0 Technologies in a Dynamic Evaluation Model for Target-Oriented Optimization. *Appl. Sci.* **2022**, *12*, 1530. [CrossRef]
100. Dalenogare, L.S.; Benitez, G.B.; Ayala, N.F.; Frank, A.G. The expected contribution of Industry 4.0 technologies for industrial performance. *Int. J. Prod. Econ.* **2018**, *204*, 383–394. [CrossRef]
101. Demir, K.A.; Döven, G.; Sezen, B. Industry 5.0 and Human-Robot Co-working. *Procedia Comput. Sci.* **2019**, *158*, 688–695. [CrossRef]
102. Zhou, C.; Bian, Y.; Zhang, S.; Zhang, Z.; Wang, Y.; Liu, Y.J. Exploring user experience and performance of a tedious task through human–agent relationship. *Sci. Rep.* **2023**, *13*, 2995. [CrossRef]
103. Montini, E.; Cutrona, V.; Bonomi, N.; Landolfi, G.; Bettoni, A.; Rocco, P.; Carpanzano, E. An IIoT Platform For Human-Aware Factory Digital Twins. *Procedia CIRP* **2022**, *107*, 661–667. [CrossRef]
104. Nguyen, T.; Tran, K.D.; Raza, A.; Nguyen, Q.T.; Bui, H.M.; Tran, K.P. *Wearable Technology for Smart Manufacturing in Industry 5.0*; Springer: Berlin/Heidelberg, Germany, 2023; Part F4, pp. 225–254. [CrossRef]
105. AL-Jumaili, H.A.; Muniyandi, R.C.; Hasan, M.K.; Paw, J.K.S.; Singh, M.J. Big Data Analytics Using Cloud Computing Based Frameworks for Power Management Systems: Status, Constraints, and Future Recommendations. *Sensors* **2023**, *23*, 2952. [CrossRef] [PubMed]
106. Blaga, A.; Militaru, C.; Mezei, A.D.; Tamas, L. Augmented reality integration into MES for connected workers. *Robot. Comput. Integr. Manuf.* **2021**, *68*, 102057. [CrossRef]
107. Mazhar, M.S.; Saleem, Y.; Almogren, A.; Arshad, J.; Jaffery, M.H.; Rehman, A.U.; Shafiq, M.; Hamam, H. Forensic Analysis on Internet of Things (IoT) Device Using Machine-to-Machine (M2M) Framework. *Electronics* **2022**, *11*, 1126. [CrossRef]
108. Yi, W.; Chi, H.L.; Wang, X.; Chan, A.P.C. A critical review of virtual and augmented reality (VR/AR) applications in construction safety. *Autom. Constr.* **2018**, *86*, 150–162. [CrossRef]
109. Rahman, M.H.; Saad, M.; Kenné, J.P.; Archambault, P.S. Control of an exoskeleton robot arm with sliding mode exponential reaching law. *Int. J. Control Autom. Syst.* **2013**, *11*, 92–104. [CrossRef]
110. Caputo, F.; Greco, A.; D'Amato, E.; Notaro, I.; Spada, S. A preventive ergonomic approach based on virtual and immersive reality. *Adv. Intell. Syst. Comput.* **2018**, *588*, 3–15. [CrossRef]
111. Obaideen, K.; Yousef, B.A.; AlMallahi, M.N.; Tan, Y.C.; Mahmoud, M.; Jaber, H.; Ramadan, M. An overview of smart irrigation systems using IoT. *Energy Nexus* **2022**, *7*, 100124. [CrossRef]
112. Runji, J.M.; Lee, Y.J.; Chu, C.H. User Requirements Analysis on Augmented Reality-Based Maintenance in Manufacturing. *J. Comput. Inf. Sci. Eng.* **2022**, *22*, 5090. [CrossRef]
113. Wang, H.; Lv, L.; Li, X.; Li, H.; Leng, J.; Zhang, Y.; Thomson, V.; Liu, G.; Wen, X.; Luo, G.; 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]
114. Caruso, G.; Re, G.M. Interactive augmented reality system for product design review. *Eng. Real. Virtual Real.* **2010**, *7525*, 115–126. [CrossRef]
115. Bordegoni, M.; Ferrise, F. Exploring the Intersection of Metaverse, Digital Twins, and Artificial Intelligence in Training and Maintenance. *J. Comput. Inf. Sci. Eng.* **2023**, *23*, 60806. [CrossRef]
116. 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]
117. Sovacool, K. How long will it take? Conceptualizing the temporal dynamics of energy transitions. *Energy Res. Soc. Sci.* **2016**, *13*, 202–215. [CrossRef]

118. Edmondson, L.; Kern, F.; Rogge, K.S. The co-evolution of policy mixes and socio-technical systems: Towards a conceptual framework of policy mix feedback in sustainability transitions. *Res. Policy* **2019**, *48*, 103555. [CrossRef]
119. Fraga-Lamas, P.; Lopes, S.I.; Fernández-Caramés, T.M. Green IoT and Edge AI as Key Technological Enablers for a Sustainable Digital Transition towards a Smart Circular Economy: An Industry 5.0 Use Case. *Sensors* **2021**, *21*, 5745. [CrossRef] [PubMed]