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Industry 4.0 and Sustainability Implications: A Scenario-Based Analysis of the Impacts and Challenges

Silvia H. Bonilla ^{1,*} , Helton R. O. Silva ¹, Marcia Terra da Silva ¹,
Rodrigo Franco Gonçalves ^{1,2}  and José B. Sacomano ¹

¹ Post Graduate Program in Production Engineering, Paulista University, UNIP, São Paulo 04026-002, Brazil; kaa_el@hotmail.com (H.R.O.S.); marcia.terra@uol.com.br (M.T.d.S.); rofranco212@gmail.com (R.F.G.); jbsacomano@gmail.com (J.B.S.)

² Graduate Program in Production Engineering, University of São Paulo, USP, São Paulo 13010-111, Brazil

* Correspondence: shbonilla@hotmail.com or bonilla@unip.com; Tel.: +55-11-96390-2641

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Abstract: The new evolution of the production and industrial process called Industry 4.0, and its related technologies such as the Internet of Things, big data analytics, and cyber–physical systems, among others, still have an unknown potential impact on sustainability and the environment. In this paper, we conduct a literature-based analysis to discuss the sustainability impact and challenges of Industry 4.0 from four different scenarios: deployment, operation and technologies, integration and compliance with the sustainable development goals, and long-run scenarios. From these scenarios, our analysis resulted in positive or negative impacts related to the basic production inputs and outputs flows: raw material, energy and information consumption and product and waste disposal. As the main results, we identified both positive and negative expected impacts, with some predominance of positives that can be considered positive secondary effects derived from Industry 4.0 activities. However, only through integrating Industry 4.0 with the sustainable development goals in an eco-innovation platform, can it really ensure environmental performance. It is expected that this work can contribute to helping stakeholders, practitioners and governments to advance solutions to deal with the outcomes emerging through the massive adoption of those technologies, as well as supporting the expected positive impacts through policies and financial initiatives.

Keywords: Industry 4.0; Internet of Things; sustainability; environmental sustainability; sustainable development

1. Introduction

Without doubt, industry has contributed to social welfare through the supply of high-quality products adapted to human necessities as well as ensuring the right working conditions for employees. Nevertheless, the pattern of current production is not environmentally sustainable [1]. In this context, a more concerned society, public sector, and non-governmental organizations are demanding that the industrial sector produce in an economically, environmentally and socially sustainable manner [1,2]. This requirement is genuine since it has become evident that production, when focused only on profit, leads to an unequal distribution of wealth, poor working conditions, the depletion of environmental stocks and the overexploitation of ecological services. The alleged right to human wellbeing, while ignoring the real limits of the biosphere, has resulted in the unsustainability of our consumption and production systems [3].

The framework of environmental sustainability restricts production within limits imposed by ecological constraints. In this way, the rate of exploitation of natural resources should not exceed the

rate of regeneration, the rate of waste generation should not exceed the assimilative capacity of the biosphere, and the depletion of nonrenewable resources should require comparable substitutes [4]. To produce within the paradigm of environmental sustainability, at least within the model of “weak sustainability”, implies in a rational allocation of natural resources, the minimization of waste or when impossible their proper treatment before adequate disposal, and the adoption of the industrial ecology approach.

On the other hand, consumers, although nowadays more aware of the finite nature of resources, are far from adopting the principles of sustainable consumption and they demand many products far beyond their real needs. When it comes to the actual purchase of sustainable products, an apparent inconsistency between attitudes towards sustainable consumption and actual behavior is observed [5]. The current scenario, which encourages increased production, contributes to the depletion of non-renewable resources, climate change, and a loss of biodiversity, among other ecological impacts.

Although the corporate vision is not unanimous, multiple successful cases and academic results have been demonstrating that producing in an environmentally proactive way is not a synonym for expense [6,7]. Companies have begun to recognize the benefits and competitive advantage associated with proactive environmental activities [8]. The resulting benefits cover a broad spectrum, such as the satisfaction of the stakeholders who currently have many environmental concerns [9], the elimination of pollution and environmental liabilities [10], and the improvement of financial performance due to opportunities in new foreign markets [11]. Moreover, a company that embraces environmentally-friendly behavior could become a supplier in a green supply chain [12] or obtain environmental certification, with the attached improvement in reputation [13].

In this complex scenario of pressing global environmental challenges, Industry 4.0 emerges from the synergy of the availability of innovative digital technology and the demand by consumers for high quality and customized products [14]. It is clear that the Industry 4.0 guiding principle was not initially focused on providing solutions to the ecological problems faced by production, but on boosting productivity, revenue growth, and competitiveness. Furthermore, Industry 4.0 has its inherent challenges to cope with in order to be successful. Some of them deal with essential requirements, such as the standardization of systems, platforms, and protocols, changes in work organization, digital security, the availability of skilled workers, research and investment and the adoption of appropriate legal frameworks [14,15]. Other challenges are related to the pressure that growing digitization is putting on traditionally successful business models [14,16].

Nowadays, Industry 4.0 is also coping with the necessity of producing within environmental constraints in order to be geared towards sustainability. The main environmental pressure that digital technologies are suffering is related to the increasing trend in energy demand, and the urgent requirement of adopting low-carbon energy systems [17].

Although it seems evident that the deployment and maintenance of both the virtual and the physical infrastructures inherent to Industry 4.0 require a reasonable environmental budget, the effect on environmental sustainability is still challenging to predict [15]. This raises a valid question: to what extent and with what delay will Industry 4.0 affect environmental sustainability, and is society prepared to deal with the environmental challenges?

The primary objective of this paper is to provide an outlook on how the inherent characteristics of Industry 4.0 and the changes it promotes affect the flow of raw materials, energy, products, waste, assets, and information, and how their modification consequently impacts either positively or negatively on environmental sustainability. This work can contribute to the understanding of possible paths towards more sustainable societies by helping stakeholders and governments to advance technical and policy solutions to deal with the outcomes that will result from the massive adoption of those technologies. Additionally, it contributes to supporting the expected positive impacts through initiatives that could range from financial incentives to value creation opportunities.

The paper is structured as follows: following this introduction, a section describes in a brief but comprehensive way the Industry 4.0 concept and its underpinning technologies. Section 3 is an

overview of previous studies relating Industry 4.0 technologies with some aspects of environmental sustainability. This is followed by the analysis of the impact on sustainability, based on a scenario approach, and the choice of each is justified and described. Thus, the effects of Industry 4.0 on the deployment and operation scenarios are explored, and the positive and negative impacts on sustainability are identified. Then, Industry 4.0 characteristics that offer a plausible opportunity for integration with the UN Sustainable Development Goals (SDG) are identified, and an overview of the opportunities that emerge from this scenario is provided to find pathways to sustainability. Finally, a credible long-term scenario is analyzed with the purpose of advancing strategic planning and anticipating public policies. The discussion is largely supported through literature research. Lastly, the main conclusions and findings are shown.

2. Concepts of Industry 4.0 and Its Underpinning Technologies

The present section provides a background with the key concepts that will assist in the development of the line of thought and may also help the readers who are not familiar with the terms.

This section is structured as follows. Firstly, we present the concept of Industry 4.0 and then its fundamental technologies. These technologies support and underpin the new production systems, leading to the emergence of properties or characteristics that will frame the production processes. These characteristics will be described in the text. Finally, we describe the capabilities/functionalities acquired or enhanced through the adoption of these technologies in an integrated way.

The concept of Industry 4.0 rose with a German government initiative in 2011, establishing it as a critical strategy for industrial production. In this vision, Industry 4.0 is part of an interconnected world, changed by the ICT (information and communications technologies) revolution. This technological context is formed by the IoT (Internet of Things) and IoS (Internet of Services), which connect the industry internally and externally through its supply chain network, while the industrial operation becomes “smart”, supported by cyber–physical systems (CPS) [14,18].

The close relation of Industry 4.0, CPS and IoT is also pointed out by other authors [19–21]. In a systematic literature review on Industry 4.0, Liao et al. found 249 papers published before July 2016 [21]. Of these papers, only three did not relate Industry 4.0 to IoT and CPS. However, it is hard to find a consensus in the literature on other Internet concepts related to the Industry 4.0 context. IoS is mentioned by [14], while [20] refers to a broader, but also abstract, concept: the Internet of People (IoP), and the Internet of Everything (IoE). The extensive literature review conducted by [22] mentions IoT without another Internet concept. In this sense, we consider IoT as the only related Internet concept without extending our analysis to IoS, IoE or IoP concepts.

Within this scope and according to the fundamental components of the Industry 4.0 idea [20], we mainly consider CPS and IoT as crucial technological components in our scenario analysis. However, the fourth industrial revolution comprises a variety of enabling technologies developed more or less at the same time as CPS and IoT that play an important role in expanding the features of the emerging production process [21]. Other enabling technologies associated with Industry 4.0 include big data, RFID, cloud computing [22] and additive manufacturing (3D printing) [23] and blockchain [24], without pretending to be exhaustive.

The formal definition of CPS adopted in this text is a system “where physical and software components are deeply intertwined, each operating on different spatial and temporal scales, exhibiting multiple and distinct behavioral modalities, and interacting with each other in a myriad of ways that change with context” [25]. CPS connects a layer of physical elements, such as machines, components, and installations, with a “cyber” layer of information systems, through sensors and actuators [19]. In other words, CPS conducts the virtualization of the operation.

CPS is a technology that allows connection and communication, such as information exchange, triggering actions, and independent control between humans, machines, and products. When integrated with manufacturing it is defined by [26] as an innovative technology in which

information from all related perspectives is carefully monitored and synchronized between the physical factory floor and the cyber computational space.

The Internet of Things (IoT) is an emerging term that combines different technologies and approaches, based on the connection between physical things and the Internet [27].

According to [28], IoT is the connection through the Internet of physical world objects which are equipped with sensors, actuators and communication technologies. IoT can have multiple application domains, such as manufacturing, health, transport, and energy, facilitating the development of new applications and improving existing uses.

The installation of proper sensors allows harvesting the signals of the physical production system for further data mining and recording. When all of the data is aggregated, this amalgamation is called “big data” [29]. Through big data, Industry 4.0 opens up new forms of value creation, particularly with the demand for innovative services and new forms of employment [14].

Cloud computing, whose central characteristic is the virtualization of computing resources and services, is described as a combination of established computing technologies and outsourcing advantages, expected to generate productivity effects in firms and growth in the economy [30]. The scalability of computing resources allows the use and payment of the resources needed without massive investment, thus helping to reduce costs and increase competitiveness.

These underpinning technologies when integrated into manufacturing, suppliers and customers in operational and strategic layers, allow the emergence of specific properties that characterize Industry 4.0. They are automation [31], digitization [31], decentralization (making independent decisions and producing locally, resulting in a reduction of organizational hierarchies) [31], virtualization (creation of a virtual copy of a factory by linking sensor data with virtual plant models and simulation models) [32], real-time data acquisition and processing and real-time data communication (thus creating the capability of immediately providing the derived insights) [14].

As a consequence, different possibilities emerge for manufacturing, in terms of the production process capabilities, the value to the final customer, or both. The main features cited in the literature are: Related to the increased value to the final customer:

- (i) Increased customization [31,33];
- (ii) Increased agility, through the decrease of inventory levels and lead times within the value chain [34];
- (iii) The tracking of raw materials and products during the whole life cycle [35];
- (iv) The emergence of novel business models which allow new ways of value creation; according to Arnold et al. [36] these are cloud-based, service-oriented and process-oriented business models. Industry 4.0 also allows innovation across business model elements: value creation, value offer and value capture [18].

Related to the production process capabilities are:

- (v) Increased efficiency [14,31];
- (vi) Increased modularity (when the structure is decoupled into subsystems with very little interdependence). This also contributes to flexibilization by replacing or expanding individual modules [32,37];
- (vii) Increased integration through data flow, thus promoting a more flexible structure and data exchange among all the elements [14,31];
- (viii) Promotion of intelligent learning analysis, which allows devices and machines to develop learning capacities and act in response to different situations based on previous experiences [38];
- (ix) Self-control and prediction (allowing predictive maintenance) [35];
- (x) Simulation and modeling of the impact of process-steps; possibility to design and test new plants before set up by virtualization [32];

- (xi) The improvement of vertical integration, since it allows the integration of the departments and hierarchical levels of the organization, from product development to manufacturing, logistics, and sales [14,39];
- (xii) The improvement of horizontal integration, as it allows global optimization of the production process across factory and company boundaries through the availability of product data throughout the entire network [14,33,39].

Related to increase value and improve production process capabilities:

- (xiii) Increased flexibility, enabling reconfiguration through adapting or changing production requirements or the addition of machine components [14,31];
- (xiv) End-to-end digital integration, allowing the integration of business processes across the entire value chain, including the factory floor and services using CPS [14,40].

Figure 1 shows a structural sketch of the technologies and capabilities described above.

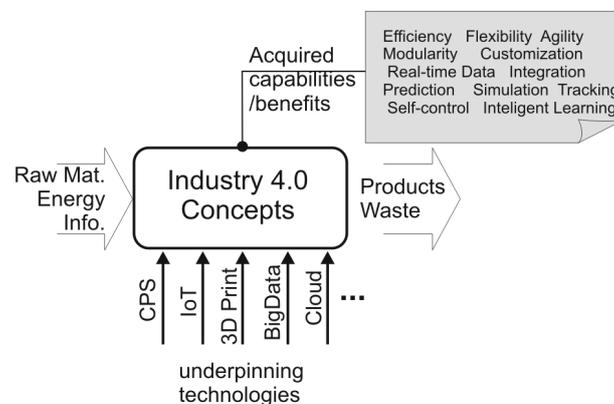


Figure 1. The underpinning technologies of Industry 4.0 and the acquired capabilities that emerge when they are adopted by production processes.

3. Overview of Environmental Sustainability-Related Research

The increasing trend in the literature dealing with sustainability within the Industry 4.0 paradigm reinforces the relevance of the topic as well as the various aspects which can plausibly be addressed. Despite the multiple approaches adopted to address the topic, there is currently a unanimous view that the long-term impacts of Industry 4.0 on sustainable development are still unclear [15]. Since the present work mainly addresses topics related to environmental sustainability, we prioritize a general overview of articles dealing with the environmental dimensions of sustainability. Lopes Sousa Jabbour et al. [41] affirm that a few emerging works provide insight into the integration of Industry 4.0 technologies and environmentally-sustainable manufacturing.

The consequences of the adoption of novel process technologies for advanced manufacturing, more precisely the additive manufacturing (or 3D printing), on industrial sustainability are addressed [42], showing the benefits but also the challenges due to the immature stage of the technology. The exploratory study based on cases shows the benefits of additive manufacturing at different stages of the life cycle by considering opportunities in terms of product design, production, use, services and repair and closing the loop. It also addresses innovative business models supported by value chain reconfiguration that will contribute to sustainable production and consumption.

According to Stock and Seliger [34] industrial value creation must be geared towards sustainability and Industry 4.0 provides immense opportunities for the realization of sustainable manufacturing. The authors carried out a state-of-art review to analyze the opportunities for sustainable manufacturing from the micro and macro perspectives through horizontal integration across the entire value creation network, the entire product life-cycle, and vertical integration. They concluded that Industry 4.0

provides an excellent opportunity for realizing sustainable industrial value creation from a life cycle perspective and supported by the intelligent cross-link.

Beier et al. [43] affirmed that there was very little research devoted to investigating the impact of digitalized industry on relevant industry sustainability aspects. The authors surveyed German and Chinese companies to investigate the expected Industry 4.0 impacts on ecological and social sustainability. The ecological dimension was evaluated through material and energy efficiency, the capacity of renewable energy implementation and the adoption of environmental strategies or standards. The findings show that the transformation is expected to positively affect ecological issues while posing challenges for the social dimension.

Corporate sustainability could be positively affected by the extensive digitization provided by Industry 4.0 by facilitating more accurate, high quality, real-time external environmental accounting and environment management accounting according to Burritt and Christ [44]. The authors offer an understanding of how the broader context of corporate sustainability could be incorporated into this agenda, hitherto undeveloped.

Kiel et al. [33] argue that the TBL (Triple Bottom Line) perspective on the opportunities and challenges that arise from the Industrial Internet of Things (IIoT) are not well understood. The authors address the implications of IIoT on TBL through an exploratory approach based on semi-structured expert interviews in 46 manufacturing companies from three leading German industries. The systematic and inductive examination suggests that IIoT-related benefits and challenges apply to all the three sustainability dimensions. The benefit to the companies that is directly related to the environmental dimension is resource efficiency.

The study by Lin et al. [45] attempts to sketch a cross-national comparative policy analysis and innovation requirements to provide policy recommendations under Industry 4.0 for sustainable development. The authors try to reveal the competition and coalition trend and anatomize the cross-strait policy content on Industry 4.0 through a comparative policy analysis across China and Taiwan. The intention is to provide a precise analysis tool for government support technology and innovation development on the national level. Both countries focus on environmental policies so that the needed infrastructure by Industry 4.0 may be developed.

The study of Müller et al. [46] examines the Industry 4.0-related opportunities and challenges as drivers for Industry 4.0 implementation in the context of sustainability and analyzes differences in company characteristics, such as size, industry sector, and the company's role as an Industry 4.0 provider or user. The authors propose a research model based on TBL comprising Industry 4.0 opportunities and challenges. The empirical results show a positive and highly significant relationship between environmental benefits and Industry 4.0 implementation. This trend is not dependent on size and industry sector.

Lopes Sousa Jabbour et al. [41] argue that the Industry 4.0-associated technologies have the unique potential to unlock environmentally-sustainable manufacturing and the authors present a study where eleven critical success factors (CSF) are identified through literature research. The CSF are considered to pose challenges and opportunities to the process of simultaneously implementing Industry 4.0 and environmentally-sustainable manufacturing. The approach adopted for sustainable manufacturing by the authors is related to "green issues" in the sense of being more focused on environmental issues.

Also in the in the context of sustainable production, a paper by Lopes de Sousa Jabbour et al. [47] proposes a roadmap to enhance the application of circular economy principles in organizations within the Industry 4.0 approach, aiming at the sustainable use of natural resources.

Gobbo et al. [48] identify the potential connections and benefits between process safety and environmental protection with industry 4.0 concepts through the measurement of keyword co-occurrence and concluded that there is much more collaborative research between environmental protection and industry 4.0 than between process safety and industry 4.0.

The potential for sustainable value creation in Industry 4.0 for the macro and micro perspective based on a literature review and expert interviews was assessed in [32]. The results show that

the value creation might positively contribute to sustainable development through new business models, new processes and a life cycle perspective. On the other hand, critical areas with expected negative contributions are related to the quantity of materials used, primary energy consumption, and working conditions.

The Industry 4.0 initiatives for supply chain sustainability in the Indian manufacturing industry were identified in [49]. Even Industry 4.0 initiatives fostering sustainable supply chains face many challenges. The research identifies 18 challenges to Industry 4.0 initiatives for developing supply chain sustainability using an extensive literature review and analyzed through a survey.

The overview of the literature encompassing Industry 4.0 technologies and the environmental dimension of sustainability highlights some approaches and methodologies. The papers presented here use different approaches to address the topic, including exploratory cases [42], state-of-the-art review [34,49], surveys in the manufacturing sector [34,43], expert interviews [32,33], literature analysis and/or exploration [32,41,44,46,47], descriptive content analysis with descriptive statistics [45], empirical study based on partial least squares structural equation modeling of the research model [46], and bibliometric networks [48].

The indicators adopted to evaluate environmental sustainability consider resource efficiency [33, 42], the efficient use of material, water and energy [34,43], the use of renewable energy [32,34,43], the adoption of environmental strategy/standards [43], the reliability of environmental cost accounting (by external environmental accounting) [44], the development of innovative environmental policies [45], the reduction of environmental impact [46], the quantity of material used, energy consumption and the amount of waste [32] and greenhouse emissions [32].

The results show that the intelligent cross-link provided by Industry 4.0 technologies enables the optimization or is expected to optimize resource allocation; the efficient use of material, energy and water [34,42,43]; facilitate better data quality and higher credibility, leading to more accurate environmental management accounting and external environmental reporting [44]; and unlock the integration with environmentally sustainable manufacturing [41].

The expected environmental benefits as pollution decreases will have a positive effect on the tendency to implement Industry 4.0 [46].

In addition, novel business models offer opportunities to positively influence sustainability through innovation and new services [32,34,42]. The potential for environmentally-added value creation is also enhanced [32,34,42,46] through life cycle integration and the application of the circular economy [47] promoted by Industry 4.0 integration.

Although there exists literature addressing the opportunities, challenges, and barriers of Industry 4.0 with regard to environmental sustainability, it remains uncertain to what extent, with which delay, and at which stage of deployment the digitization of industrial production will promote or hinder transformations that will affect environmental sustainability. We think that the technology has not been sufficiently explored from a sustainability perspective due to its novelty and the different degrees of implementation within countries, and although it seems promising, its long-run impacts are uncertain.

4. Materials and Methods

The line of thought adopted to address the problem is based on a theoretical analysis to evaluate the positive or negative impacts of the Industry 4.0 production context and its underpinning technologies on environmental sustainability aspects. To this end, we consider the necessary flows of all production activities: raw material (RM), energy (E) and information (INFO) as input flows; and products, waste, and end-life products (END) as output flows. Four scenarios drive our analysis as will be explained in 4.2.

4.1. Outlining the Environmental Sustainability Framework Adopted

Environmental sustainability is an ideal state, and it is only possible to quantify the distance from the ideal point of sustainability [50]. Throughout the text, we refer to the impact on sustainability

in the sense of determining whether there is a decrease or increase of the distance towards the ideal sustainable state. The method used to determine this trend, namely to distinguish whether the actions are contributing to decreasing or increasing the distance from sustainability, was through the use of some relevant parameters.

Since the objective of this work was not to quantify or measure indicators, but a systemic and prospective exploration, we were faced with the challenge of selecting universal parameters, easy to understand, ubiquitous and almost intuitive, to infer the influence they experience as a result of any type of activity. Moreover, they must be able to be extrapolated from the micro to the global scales, thus enabling inferences about the history and disturbance of ecosystems and life cycles.

Additionally, the concept of sustainability is linked to extensive properties, since it depends on the availability of limited resources within the biosphere. In this way, Bastianoni et al. argued that it is not possible to assess sustainability by using intensive parameters because the problem is strongly correlated with the size of the system [50].

By focusing on a production perspective, productivity relies on the ecosystem's ability to provide services and resources, and non-sustainability means a systematic degradation of this ability [51]. However, to measure the degradation due to production-related activities is not straightforward, since impacts have a delay between the cause or "upstream" activity and the observed effect [51]. In this way, environmental impact evaluation is not considered here as a straightforward methodology to access the influence of manufacturing activities on sustainability.

Also from a production perspective, some tools deal with sustainability within a range of spatial dimensions (from micro to more systemic scales). According to Robèrt, there are more than 60 codes [51]. However, most of the tools emerged from the mathematical aggregation and weighting of other parameters, a fact that hinders a correct prevision of the effect of activities. However, a comparison of some of the recognized tools applied in addressing organizational sustainability allows the extraction of common environmental parameters that are considered as single indicators or within an aggregated index.

From a comparison by Goodland and Daly that compiles some examples of proposed sustainability performance measuring systems, we found a subset of parameters that have the desirable specific characteristics [52]. They are omnipresent, they allow us to establish a direct cause–effect relationship, they are well-established and easy to control, they are easy to handle, and their trends due to anthropogenic activities are easy to foresee. Additionally, they are scalable to enable correlation with global theories of environmental sustainability. The set—composed of material, water and energy use, waste and air pollution (and greenhouse emissions)—is directly related to the paradigms of environmental sustainability. Thus, the flows of material, water, energy, waste and pollutants involved in production should be constrained within the requirements stated by the paradigm considered in the sustainability framework adopted. The biosphere acts as a resource provider and as a sink for wastes and pollutants [53]. The basic definition of environmental sustainability relies on the input–output rule, determining that waste emissions from a project must be within the biosphere's assimilative capacity and resource inputs must be within the regenerative capacity of the natural system that generates them [53].

The evaluation of the influence of Industry 4.0 activities on sustainability will be carried out employing an analysis of the parameters mentioned above. No quantification will be accomplished, but rather a comparison regarding the necessary flow of all production activities between the actual state and the future stages in the four perspectives of analysis (next Section 4.2). The comparison requires a certain degree of abstraction in the cases in which there is a lack of literature relating cause–effect. In these cases, discussion among the authors and the exchange of ideas helped evaluate the effect on the flows considered and thus establishing a trend in sustainability terms.

The principles of Industry 4.0 promote the real-time sharing of information, allowing the rapid modification of production and the monitoring and performance control of production lines through connections between machines, devices, and supply chain tiers [41]. The collection of data on usage is

also one of the goals of Industry 4.0, since it can help companies to understand patterns of consumption, improve the customization of products, and enhance the service aspects of products [41]. Accordingly, it is possible to affirm that Industry 4.0 relies on information. Not only the information generated, but also the transmission, storage, and analysis are material-dependent and energy-intensive [54–56]. The basic flows are subject to changes that will affect the environment either positively or negatively, as they contribute or negatively interfere with environmental sustainability. The literature also confirms that the digitalization of industrial production will influence environmental production factors such as resources and energy consumption, as found in the results of surveys conducted in companies in China and Germany [43].

4.2. Selection of the Analysis Scenarios

The scenarios to carry out the analysis were selected by setting the basic elements of Industry 4.0 relevant to expected future states and through a description of the consequent necessities/demands faced and the opportunities that emerge. The necessities and opportunities, identified mainly through the literature review, affect the environmental sustainability through the relevant flow modification. As a “scenario”, we consider a set of conditions, variables and boundaries that drive a future (prospective) context of analysis. The scenario-based approach has been used in environmental impact analysis, sustainable energy future and other prospective studies [57–59].

In this sense, a scenario involves a context boundary to restrict the analysis to a well-delimited frame of time and variables or agents, to describe a possible near or long-term future. However, the four presented scenarios are not alternatives for the future, as pointed out by [60], but complementary, representing four different contexts and times of analysis: the near future, medium-term future and long-term, as well as a SDG-related discussion scenario.

The scenarios are:

- **Industry 4.0 Deployment:** refers to the evolution from the current industry level to the Industry 4.0 level. This includes the infrastructure necessary for the implantation of the fundamental elements to reach the operational condition. In this case, RM and E are related to the infrastructure. END is related to obsolete devices and equipment.
- **Industry 4.0 Operation:** refers to the operational stage, on which companies are transforming inputs (RM, E, INFO) into outputs. Under this scenario, we discuss the Industry 4.0 differentials or advantages created by the underpinning technologies and their effects on input and output flows.
- **SDG Compatibility:** discusses the possibilities and impacts from the point of view of the UN Sustainable Development Goals (SDGs). Our analysis involves the subset of the SDGs more related to environmental goals to support the discussion.
- **Long-Term:** this scenario involves a prospective analysis, or projection, of possible positive and negative long-term and growing effects of the impacts on sustainability.

The Deployment Scenario is formed by the basic elements that constitute an Industry 4.0 context. A previous high level of automation is one of them [14,20], and this is a fundamental condition for achieving the Industry 4.0 level of productivity and flexibility [19]. Second, the industry requires the digitization of its process, with IoT, CPS and real-time data acquisition, analysis, and control to become “smart” [14]. Both IoT and CPS are considered the key elements to the integration—vertical and horizontal—of the production process that is the fundamental aspect that characterizes Industry 4.0 [14,19,37]. In this sense, we can consider automation, digitization, and integration the key aspects of the Deployment Scenario.

The Operation Scenario is set by the production objectives acquired with the operation of Industry 4.0, and the benefits offered by the underpinning technologies. As pointed by [14], the operation becomes “smart” with the vertical and horizontal integration created by IoT and CPS. “Vertical integration refers to the integration of the various IT systems at the different hierarchical levels” from the lowest level of sensor and actuators to the highest level of management information systems,

while “horizontal integration refers to the integration of the various IT systems used in the different stages of the manufacturing and business planning processes that involve an exchange of materials, energy and information” [32]. Smart production is also achieved with real-time data acquisition and processing, to monitor, control and optimize the production flow [14,20], including advanced data mining and big data analysis (BDA) [37]. Additive manufacturing, also called 3D printing, is another technology that composes the operation scenario, especially related to flexibility, customization and on-demand production [23,61]. Finally, Blockchain and smart contracts are brand new technologies in Industry 4.0, but considering what is occurring with the crypto-currencies (based in Blockchain) its vast energy consumption is an aspect to be considered [62].

The elements of the SDG Scenario are defined analogously to the previous scenario. Additionally, in this scenario, is also relevant to consider innovative business [14,19,61] as a key element. The integration with sustainability principles is achieved via the setup of a sustainable development goal platform that considered SDGs 7, 9, 12 and 13. Within this integrative scenario we identified relevant actions where the integration could contribute in a planned way to environmental sustainability.

Finally, the Long-Term Scenario is composed of elements derived from the literature and previous scenarios organized in such a way that their analysis enables us to address the question. This scenario requires a prospective analysis since it depends on the greater or lesser compliance with the SDGs. Accordingly, two opposite alternatives depending on how some key factors (extracted from the literature and from discussion among authors) conduct the long-run evolution. Each key factor is analyzed by assuming a positive and a negative trend towards sustainability. It represents the opposite expected situation that Industry 4.0 technology will face as a consequence of environmental pressures and requirements.

Industry 4.0, driven by its unique junction of characteristics, will affect the systems where it operates in multiple ways. The “filter” imposed by each scenario or analysis perspective acts in a restricting way, by directing Industry 4.0 actions within a specific constraint such as: (a) the stage or degree of implementation (evidenced when comparing actual or pre-Industry 4.0 stages to deployment and operation stages); (b) the degree of compliance with or commitment to the SDGs (evidenced when comparing the as-usual operation stage with the SDG scenario); and (c) time (evidenced when the comparing operation stage with the long-term scenario). In this way, the chosen scenarios correspond to different conditions; they evidence not only two different stages of implementation (initial deployment stage vs. operation stage), but also the temporal evolution from the initial scenario to the long-term scenario.

In each scenario, the pressure exerted by Industry 4.0 activities will manifest differently, by means of either new demands/necessities or new opportunities.

The Industry 4.0 activities relevant to each specific scenario and the linkages with environmental sustainability are explored through a cause–effect framework. As Figure 3 shows, the effects resulting from the Industry 4.0 context (displayed as INDUSTRY 4.0) within each scenario (block termed as SCENARIOS) lead to direct or indirect changes in the state of each system. This state is defined by the basic input and output flows (block termed as FLOWS) relevant to the concept of environmental sustainability. They will be affected as a consequence of Industry 4.0 actions within the scenarios. The essential elements relevant to environmental sustainability are the flow of raw materials, energy, products, waste, end-life products, and information. An environmental budget is supposed to support all these flows and is affected by production activities. All kinds of material, as well as energy flows, are more easily perceived to be strongly dependent on environmental resources and services since they rely directly on raw materials, mineral ores, oil, water bodies, and land use. Information flows are also dependent on environmental resources [54–56], although the perception of this dependence may be less evident. The inherent principles of Industry 4.0 promote real-time shared information, allowing the rapid modification of production, as well as the monitoring and control of the performance of production lines through connections between machines, devices, and supply chain tiers [41].

The collection of data on usage is also one of the goals of Industry 4.0, since it can help companies to understand patterns of consumption, improve the customization of products, and enhance the service aspects of products [41]. Not only the generation of data but also the transmission, storage, and analysis are material-dependent and energy-intensive. The changes that may occur in these essential elements can affect the environment either positively or negatively, as they contribute or negatively interfere with environmental sustainability. The discussion will enable us to recognize that sometimes the changes suffered by the flows are not always related to quantity (namely, an increase in raw materials or an increase in data collection). Changes related to the nature of flows can also occur, that is, the amount of energy flow may not decrease, but may depend on renewable sources, thus altering their nature. Flows of information or data can be considered more reliable, and data acquisition is becoming more sophisticated, thus changes in quality are also considered.

Finally, the fourth block in Figure 3 (RESPONSE) corresponds to the trend of the impact on environmental sustainability caused by the activities represented in the first block. Figure 2 shows a pictogram of the scenarios.

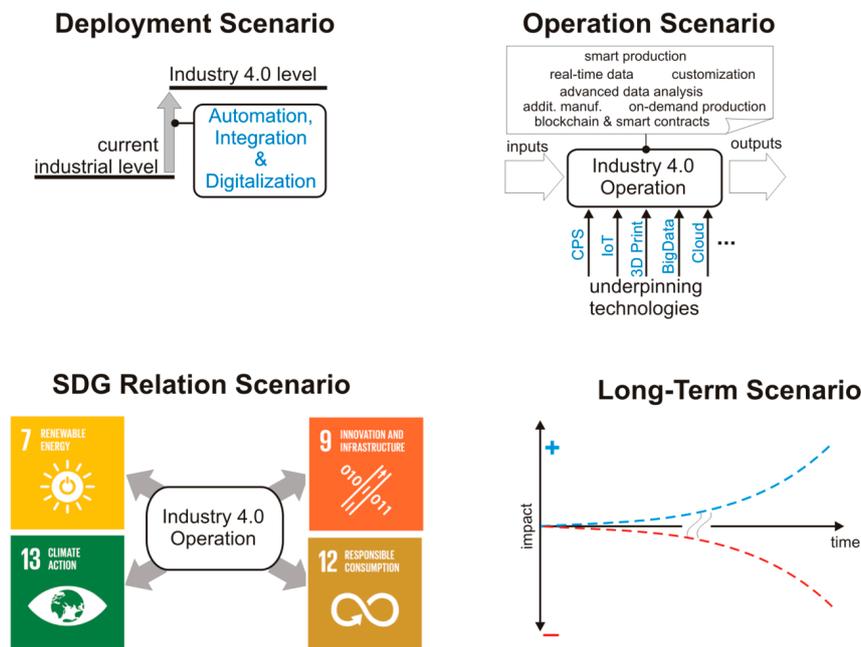


Figure 2. Conceptual representation of the analysis scenarios.

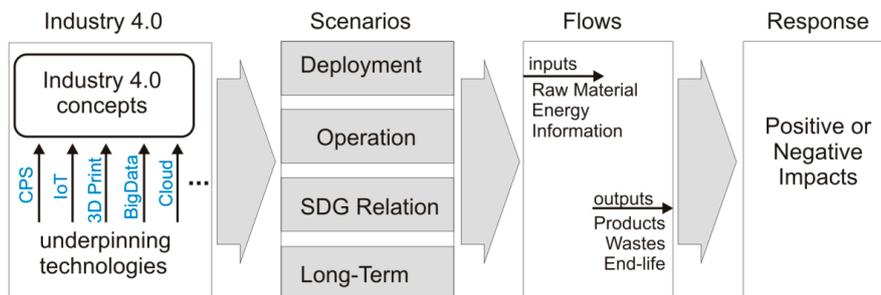


Figure 3. The line of thought adopted and the causal relationships among the different elements and blocks. The first block represents the characteristics and technologies inherent to Industry 4.0; the second represents the four scenarios explored in the text, whereas block 3 displays the flows that suffer direct influence from the necessities or opportunities generated in each scenario. The response regarding the positive or negative impacts on environmental sustainability is represented in the last block.

5. Results and Discussion

This section provides a concise description of the experimental results, their interpretation, as well as the experimental conclusions. It comprises four subheadings, one for each scenario.

5.1. Deployment Phase Scenario

It is evident that the spread of Industry 4.0 will face inherent environmental challenges. At least, new demands to ensure the successful implementation of the technologies will emerge.

As stated by Müller et al. [18] the integration to CPS demands the purchase of new machinery, the integration of sensors and software, and high computing capacities. The required infrastructure to support digital transformation will rely on natural and human-made resources.

From a life cycle perspective, a massive adoption of Industry 4.0-related technologies entails raw materials, water and fuels for manufacturing all of the new machinery and devices as well as resources (fuels, land and ecological services) for the disposal of obsolete equipment. An exploration of the literature retrieved evidence that enables us to propose cause–effect relationships regarding the deployment and the environmental sustainability trend.

Regarding material flows, the present scenario relies on a supporting environmental budget since electronic devices, robots, computer terminals, and sensors demand material and energy resources in their manufacture and deployment. According to the International Federation of Robotics (IFR), robot sales increased by 16% to 294,312 units in 2016 due to the ongoing trend toward automation [63]. The IFR also states that Chinese companies are buying enormous quantities of robots thus installing more manufacturing robots than any other nation [63]. Digitization relies on hardware that requires scarce raw materials, such as lithium and heavy rare earth [64], that are difficult to extract, handle, purify and recycle. An increase in demand for scarce raw materials is expected due to the dissemination of digital technologies.

An increased use of materials can be expected due to these new technologies as well as to the upgrade of production facilities, machines, and other resources with additional ICT, in particular, sensors [32]. The implementation of an integrated production infrastructure implies the consumption of new devices, mainly sensors and actuators [14]. It also entails the disposal of obsolete equipment that cannot be integrated with new systems, increasing waste, especially electronic waste.

The obsolescence of machinery and equipment as a consequence of automation and digitization, leads to the necessity of equipment replacement. According to the level of automation/digitization, the degree of equipment to be replaced within a company will change. It is expected that about 40 to 50 percent of existing equipment will be replaced in the course of Industry 4.0 [65]. It is important to consider that those percentages were estimated for developed countries such US, Germany and Japan, which are at a higher technological stage.

Regarding energy consumption, an increase in primary energy consumption is expected due to the manufacturing of product-related ICT [32].

Table 1 organizes the above discussion in an attempt to provide evidence of the cause–effect trend. Accordingly, it shows how the elements relevant to the scenario are expected to impact on environmental sustainability. The table's first column is entitled Industry 4.0 elements. The second column shows the expected necessities or the opportunities that will be generated from deployment of the Industry 4.0 technologies. The effects on the relevant flows are briefly described in the third column, while the last column identifies the trend of the expected impact. When possible, the life cycle perspective was adopted to infer the effect on the flows. Accordingly, not only the direct effect is estimated but also that related to other phases of the life cycle. A clear example of this life cycle perspective is the estimated effect on energy flows, which is related to manufacturing phase due to the crescent trend towards the manufacturing of new machinery.

Table 1. Overview of characteristics of Industry 4.0 at the deployment phase and their impact on environmental sustainability based on the above discussion.

Industry 4.0 Elements	Needs/Opportunities	Effect on Flows	Impact Trend
Automation	Increased equipment demand	Increased raw materials flow in their manufacturing	Negative
		Increased energy flow in their manufacturing	Negative
	Potential equipment obsolescence	Increased flows of end-life products to disposal, recycling	Negative
		Increased fuel flows for transport (towards disposal or recycling)	Negative
Digitization	Increased device demand	Increased raw materials flows in their manufacturing (Li and rare earth)	Negative
		Increased energy flow in their manufacturing	Negative
	Potential equipment obsolescence	Increased flows of end-life products to be disposed, recycled	Negative
		Increased fuel for transport (towards disposal or recycling)	Negative
Integration (implementation)	Increased devices demand	Increased raw materials flows in their manufacturing (Li and rare earth)	Negative
		Increased energy flow in fabrication	Negative
	Potential equipment obsolescence	Increased flows of products to be disposed, recycled	Negative
		Increased fuel for transportation (towards disposal or recycling)	Negative

It is important to notice that all the effect on flows in this scenario were evaluated by assessing the life cycle, thus considering mining and the manufacturing of equipment/devices. The necessities generated within this scenario as a consequence of the demand for new devices will add a burden to the environment [17]. Thus, a negative impact on environmental sustainability is expected as discussed above and listed in Table 1. Additionally, the increasing trend in machinery obsolescence due to new skill necessities leads to an increase in landfill demand when recycling is out of the question.

The discussion also provides evidence of the challenges to be faced in environmental terms and shows relevant or potential problems that public policy, society, academia, government, and international organizations should consider. In this way, the recycling of rare earth to minimize their extraction and the consequent environmental disturbance is a topic that deserves attention. Innovation directed towards research on the minimization or substitution of rare metals is strongly encouraged. The retrofitting of manufacturing equipment when possible can be encouraged [34] as a way to enable material and energy savings.

5.2. Operation Scenario

This scenario describes the expected situation under Industry 4.0 operation and how it will affect resources, raw materials and energy consumption, waste generation and data collection, storage, and analysis.

As described by Qin et al., the operation of Industry 4.0 will involve not only a connected and automatically exchanging information system, but also a system that has become conscious and intelligent enough to predict and maintain machines; to control the production process, and to manage the factory system in a decentralized and interdependent way [37].

The collection of impressive amounts of data and the opportunity to analyze them to perform more advanced processes are crucial for Industry 4.0 [66].

While the Internet of Things (IoT) allows the acquisition of real-time energy consumption data and the analysis at the machine and production line level to improve energy-aware decision-making [67], the smart production systems will require massive data centers to process and support their network needs [68]. Thus, an increase in primary energy consumption focused on data centers and the processing of big data in the cloud is expected [32]. The necessity of the constant monitoring and

adaptation of the production process demands dynamically configurable processes with the expected increase in primary energy consumption [32].

Table 2 displays the main needs expected for the operation scenario. The demands generated by operation within the Industry 4.0 technology framework mainly affects energy flows according to the literature exploration.

Table 2. Overview of the main requirements of Industry 4.0 at the operation phase and their impact on environmental sustainability based on the above discussion.

Industry 4.0 Elements	Needs	Effect on Flows	Impact Trend
Smart production:			
<ul style="list-style-type: none"> • IoT and CPS integration • Real-time data control 	Demand for massive data centers	Increased energy flow	Negative
On-demand production and customization	Dynamically configurable processes	Increased energy flow	Negative

On the other hand, the digitization of manufacturing processes can offer opportunities for energy saving [69]. Shrouf and Miragliotta describe six sets of benefits due to IoT adoption and integration between real-time data and the company's information technology tools and platforms, in order to improve energy efficiency [67]. The application of optimization software tools can achieve energy savings, thus reducing up to 30% of the consumption for a real industrial robot trajectories [70]. Besides the approach of improving energy efficiency utilizing the optimization of a single machine or the whole manufacturing process, there exists the possibility of smart energy allocation promoted by the horizontal integration of factories and enterprises. Energy saving for production management is performed through intelligent optimization algorithms to optimize total energy consumption with a big data processing platform [71].

Industry 4.0 can provide support through continuous resource management due to the detailed information availability on each point of the production process [69]. Accordingly, the monitoring of real-time data enables the awareness of resource consumption and responsive production management.

In addition, the emergence of novel technologies can improve material savings, as is the case for additive manufacturing, known as 3D printing. Additive manufacturing creates products layer-by-layer, it is inherently more resource efficient and less wasteful than traditional subtractive methods due to its ability to reuse waste material [42]. The technology is promising since a variety of polymers, metals, ceramics, and composites can be used, furthermore, although the first applications of it were in the area of rapid prototyping and then tooling, they are increasingly being used for direct manufacturing [42]. Doubts arise due to the variability of results relating energy efficiency when compared with other methodologies, but the energy footprint can be low for processes that do not involve lengthy processing at elevated temperature [32,72]. Even so, due to the frequent use of laser technologies and when starting from powdered material, additive manufacturing processes are still energy inefficient [32]. In addition, 3D printing does not require ancillary, sustainability-impacting cutting fluids, casting release compounds or forging lubricants [72]. Additionally, additive manufacturing processes enable a variety of end-of-life practices, producing individual spare parts to extend lifespans [32].

Additive manufacturing techniques influence maintenance, logistics and contribute to the flexibilization necessary for on-demand customized products. In this way, energy and fuel (and the resulting carbon emissions) are saved when a part is repaired or refurbished rather than being replaced and disposed, and transportation is decentralized [69,72].

Predictive and remote maintenance, another characteristic of Industry 4.0 promoted by real-time monitoring, can also positively affect the environmental burden. Preventive and predictive maintenance promoted by big data analytics extends the lifespan of machinery, thus minimizing end of life waste [35].

On-demand customized products, one of the drivers of Industry 4.0 development, enables two approaches regarding its impact on environmental sustainability. The more pessimistic approach relies on the thinking that the easy availability of customization may foster the need to possess more objects, feeding a short-term hedonism, a sense of ephemeral happiness. On the other hand, the customized product may eliminate undesired or unneeded functionality for end users. However, deeper examination of this question is beyond the scope of this paper. Since the physical realization of each function requires material resources and energy for digital solutions, the reduction of functionality is supposed to positively impact on the environment [73].

Mass customization leads manufacturing companies to collect many consumers' personalized data from the web in real time, while also managing more types of relevant data [74] as well as subjective data feedback from consumers [66].

Industry 4.0 can also foster disruptive business models where not products but functionalities, maintenance and services will be offered to consumers [32]. These new business models can extend the life-cycle of products, since new functionalities could be added in a modular way without replacing the whole device.

Blockchain technology can reshape business models through integration with Industry 4.0 by keeping and creating records and enforcing contracts across industries [75]. Since Blockchain is transparent, immutable and irrevocable [75], it allows the creation of reliable information. However, the significant amount of energy it consumes is still a limitation to be taken into account when dealing with environmental sustainability. Furthermore, current consensus algorithms like proof of work waste too much electricity [76]. Nevertheless, this affirmation is not unanimous [62].

Table 3 presents an overview of the Industry 4.0 elements addressed in exploring this scenario and capturing their effect on environmental sustainability. From the opportunities generated by Industry 4.0 technologies during operation, the cause–effect impact on the relevant flows is shown in the third column. The results are extracted from the above discussion.

Table 3. Overview of the main characteristics of Industry 4.0 in the Operation Scenario that impact on environmental sustainability.

Industry 4.0 Elements	Opportunities	Effect on Flows	Impact Trend
Smart production: • IoT and CPS integration • Real-time data control	Vertical integration	Availability of reliable data about materials flows	Positive
		Availability of reliable data about energy flows	Positive
	Horizontal integration	Availability of reliable data about material consumption along the life cycle.	Positive
		Availability of reliable data about energy consumption along the life cycle	Positive
Collection of data from consumers	Availability of subjective data	It depends	
Big Data Analytics	Optimization of material consumption/eco-efficiency	Decreased material flow in manufacturing	Positive
	Optimization of energy consumption/eco-efficiency	Decreasing energy flows at the factory	Positive
	Predictive maintenance/Remote maintenance	Decreased energy flows	Positive
Additive manufacturing	Prototyping Tool and mold manufacturing Final product manufacturing Part manufacturing	Decreased waste	Positive
		Decreased materials flow	Positive
		Decreased waste	Positive
		No cutting fluids and forging lubricants	Positive
		Increased energy flows	Negative
On-demand production and customization	Elimination of the undesired functionalities of products	Decreased material and energy	Positive
	Disruptive business model/functionality and services	Extended life cycle of products/decreased end-of-life products	Positive
Smart contract/Blockchain technology	Transparency/decentralization/reliable information	Increased energy flows	Negative

In this scenario, the increase in energy consumption seems to be the problem to deal with. Even with the possibilities offered by energy optimization due to algorithms and data analytics, energy consumption is a challenge that must be faced in order to successfully contribute to environmental sustainability. However, all the elements of the scenario positively contribute, at least partially, towards environmental sustainability. In this context, technological research, policy-making initiatives, and fostering innovative business models to add sustainable value are welcomed to reinforce the positive aspects and to overcome negative aspects.

5.3. Scenario of Industry 4.0 and Sustainability Integration

The analysis was carried out by establishing an integration platform where Industry 4.0 and environmental sustainability (and their objectives and tools) were able to interact. The transition process towards sustainable societies must be appropriately planned, directed and controlled, to ensure the success of the transformational journey [3]. Within this framework, the objective was to identify those relevant elements and characteristics of Industry 4.0 technologies that could contribute in a planned way to attaining the objectives inherent to environmental sustainability. In the first two analyzed scenarios, the positive influence on environmental sustainability does not emerge from purposely planned actions in this direction. Moreover, they can be considered as positive secondary effects derived from Industry 4.0 activities. The present scenario differs since the integrated platform is the key driver and the positive environmental effects are the goals.

The integration platform in this scenario is constructed through the identification of synergy points between Industry 4.0 and sustainability. To set a well-supported platform of integration, we extracted from those Sustainable Development Goals directly linked to environmental aspects the characteristics that can be interrelated to the Industry 4.0 elements. The Sustainable Development Goals (SDGs) were adopted by the UN Sustainable Summit to guide international efforts towards Sustainable Development until 2030 [77]. The establishment of goals is a necessary condition to begin the journey towards sustainability. However, the goals will undoubtedly evolve as humans become capable of considering long-term goals and learn more about the linkages between the systems and dimensions of sustainability [3].

Of the seventeen SDGs, four were selected due to their close relationship with environmental issues. Additionally, they should be capable of integrating their objectives with actions intrinsically related to production processes. In this way, the following SDGs were chosen to compose the integration platform: SDG#7 “affordable and clean energy”, SDG#9 “industry, innovation and infrastructure”, SDG#12 “Responsible consumption and production” and SDG#13 “climate actions”.

The elements of Industry 4.0 that would feasibly proactively interact with the selected SDGs to create new opportunities to achieve sustainability targets are the same as those in the operation scenario, plus novel business models as an additional key element. The operations scenario showed that there exist some deficient aspects to be improved and others to be optimized to purposely contribute towards sustainability. This improvement will be discussed in this scenario, emphasizing opportunities for the integration with SDGs.

IoT and CPS allow increasing energy saving opportunities, which can be accomplished through the substitution of technologies, the application of software for energy optimization and adaptations in business processes.

As stated in [73], the sustainable energy transition and Industry 4.0 share an important characteristic, namely both are highly influenced by technological innovations.

Smart grids allow real-time decisions in the choice of energy sources. Moreover, real-time monitoring enables energy supply sources to automatically switch to low or no carbon emissions depending on the energy costs [44]. The combination of real-time data and the automation-enabled temporal flexibility offer transparency for optimizing the company’s energy management and smart grid setting benefits either by consuming and storing energy or, on the contrary, by reducing their consumption (in case of energy shortage) on demand [73]. The smart grid concepts involve the

adoption of an information system to match energy consumption with production [48]. Smart grids supported by the potentials of information and communication technologies can efficiently manage the generation, delivery, and consumption of electricity from different decentralized sources of electricity, as well as integrating renewable energies to meet the varying electricity demands of end-users [78].

Full production information will assist product development from design to disposal, promoting the life cycle perspective. Additive manufacturing can improve and optimize material and design selection to positively impact the use phase, allowing recycling or remanufacturing through the whole life-cycle. The case of General Electric's LEAP engine is well-documented, where 3D-printed allows the augmented durability of the component while reducing its weight by 25%, as well as attaining an optimized geometry to achieve higher combustion efficiency with consequent fuel and CO₂ emission savings [42]. As demonstrated by [79], the 3D printing technology shows remarkable potential for technological sustainability. A weak point of additive manufacturing, namely the recyclability of materials, which is largely unexplored, is assumed to be increasingly deployed [32].

The quality, quantity, and accuracy of information gathered within the Industry 4.0 paradigm will contribute to the release of reliable data capable of feeding national databases, helping policymakers and contributing to responsible consumption. At the corporate level, sustainability reports supported by credible environmental accounting could present reliable data, avoiding the accusation of greenwashing, as stated by [44]. Moreover, the lower human interference in the data collection process, the more transparent the information for stakeholders will be.

Blockchain technology has been cited as having a great significance in the development of environmental sustainability, with the long-term goal of reducing the effects of climate change [24]. The Blockchain technology, which has proven to be compatible with Industry 4.0, allows supporting an emissions trading application framework [80].

Regarding disruptive business models, [81] explored the synergistic relationships between the circular economy and big data, and how it can enhance social and environmental sustainability, enabling the decoupling of environmental burden and economic growth.

Since the SDGs present interlinks, a multiplier or synergic effect is observed on the other four approaches when we focus on one of them. In this way, Table 4 shows the integration of the approaches and the opportunities for improvement, as well as the final effect on flows.

Table 4. Integration of the approaches between the SDGs and Industry 4.0 elements and the opportunities for improvement that emerges from that integration.

SDG	Integration through Industry 4.0 Elements	Enhanced Opportunities towards Environmental Sustainability	Effect on Flows
SDG#7 Affordable and clean energy	<ul style="list-style-type: none"> • Digitization (IoT and CPS) • Real-time monitoring and data collecting • Big data analytics 	Implementation of smart grids	Decreased energy flows
		Implementation of life cycle assessments	Increased renewable energy
SDG#9 Industry, innovation and infrastructure	<ul style="list-style-type: none"> • Digitization (IoT and CPS) • Real-time monitoring and data collecting • Additive manufacturing • Novel business models 	Improve weak points of additive manufacturing (energy and recyclability)	Decreased energy flows Decreased material flows Decreased waste flows
		Extend integration with the circular economy	Decreased end-of-life products
SDG#12 Responsible consumption and production	<ul style="list-style-type: none"> • Digitization (IoT and CPS) • Real-time monitoring and data collecting • On-demand production/customization 	Implementation of reliable and transparent sustainability reporting on-demand parts manufacturing services instead of tangible product	Increased reliable data Decreased material flows Decreased waste flows
SDG#13 Climate actions	<ul style="list-style-type: none"> • Digitization (IoT and CPS) • Real-time monitoring and data collecting • Big data analytics • Blockchain 	Implementation of smart grids	Decreased energy flows
		Implementation of life cycle assessments	Increased renewable energy
		Blockchain-enabled emission trading	Decreased GHG emission

We can expand the analysis by suggesting that innovation supports not only the sustainable transition, but also other sustainability-driven actions. Although not all requirements have been translated into technical solutions, innovation supported by appropriate regulations is expected to

foster integrated environmental solutions for digital manufacturing. If, to date, innovation seems to be the main driver of Industry 4.0, the integration with environmental sustainability will promote eco-innovation. This practice is already positively impacted by the development of lighter materials, design for the environment, nanomaterials, algorithms for energy optimization, disruptive business models and integration with more sustainable economic models. As an example, this involves selling the functionality and accessibility of products instead of only selling the tangible product [34].

5.4. Long-Term Scenario

It is not trivial to assess the longer-term scenario, since not only one future trend is conceivable from a projection of the present situation. Nowadays, Industry 4.0 is still at an incipient stage, spatially concentrated and mainly adopted by multinational enterprises.

Even with the existing risks and challenges, it is believed that for business management, Industry 4.0 can be competitive in the long term [33] while creating sustainable value.

Some of the factors that emerge from the literature and further discussion among the authors could change the trend towards sustainability. Accordingly, an unskilled workforce is considered a key factor, and predictions vary as to how industry and the government will deal with the workforce that does not match the new profile. Kagermann et al. already mentioned this social challenge [14].

If the adoption disseminates in a geographically distributed form and among companies of different sizes, the future trends will vary.

In the long term, the way that Industry 4.0 will impact environmental sustainability is not as straightforward as in previous scenarios. The reaction of society, business, and governments to the new paradigm will be critical in directing the types of impact.

If the Industry 4.0 dissemination does not occur in a geographically homogeneous way, there will be niches of economically and socially disadvantaged countries with a consequent increase in the gap between developed and developing countries.

As one of the concerns of Industry 4.0 is customization [31], consumers in economically more productive societies can disregard responsible consumption, motivated by the availability of on-demand customized products. Additionally, new necessities inherent to the new technological demands will arise, such as devices, drones and sensors, which will require materials for their manufacturing [32]. The infrastructure to maintain and provide secure data transfer will also concentrate a large amount of resources and energy [32].

Many factors may influence the long-term development of Industry 4.0. However, we believe that the degree of synergy achieved between social and environmental SDGs and the homogeneous geographic distribution of the technology will be decisive in the proactive interaction with environmental sustainability.

Although it has been argued that Industry 4.0 can be a facilitator of environmental sustainability when integrated with the SDGs, the perspective could change to a pessimistic scenario if integration were not achieved. Within the pessimistic scenario, the combination of some factors such as unskilled labor, high obsolescence, high consumer demand and low eco-efficiency will have a negative impact on environmental performance [42]. An additional factor that can drive the long-term response is the starting point of the industrial structure, since it might be affected differently and the quality of changes may vary between countries [43]. New business models, in which social media information could be used to promote pro-environmental actions [46] and select products that are environmentally friendly [82] should be promoted to avoid the pessimistic scenario. Fostering feedback from customers and employees could also be driven to value co-creation [83].

The exchange of information and technology will be crucial to involving developing countries and avoid the unsustainable trend.

In 2035, the demand solely for emerging technologies could even be double that of primary production in 2013 for three metals: lithium, dysprosium/terbium, and rhenium [64]. For these metals, the increase in demand due to technological change is significantly higher than the increase in demand

due to global economic growth. In this way, substitutes or proper recycling and purification will require technological innovation and research.

Table 5 shows an overview of the two likely long-term scenarios, namely the optimistic and the pessimistic scenario according to the key factors analyzed above. The social and technological response to the shortcomings, demands, and challenges will propitiate one of the trends.

Table 5. Overview of two conceivable long-term scenarios from an optimistic and a pessimistic projection. The type of response to challenges will direct the trend.

Characteristic of the Projection	Key Factors	Response	Impact Trend
Optimistic	Device demand	Increased recycling	Positive
	Raw material demand (Li, etc.)	Research for substitutes	Positive
		Increased recycling	Positive
	Consumer concerns	Aware	Positive
	Unskilled workforce	Focus on training and formation	Positive
	Company infrastructure	Homogeneity in terms of automation and digitization	Positive
	Novel business models	Promote value co-creation	Positive
		Promote pro-environmental markets	Positive
	Geography	Spatially homogeneous adoption of the technology	Positive
		Exchange of technology between developed and developing countries	Positive
Pessimistic	Device demand	Increased raw materials flow in fabrication (Li and rare earth)	Negative
	Consumer concerns	Unaware	Negative
	Company infrastructure	Heterogeneity in terms of automation and digitization	
	Geography	Spatially concentrated adoption of the technology	Negative
		Technology concentrated in developed countries	Negative
	Equipment obsolescence	Increased flows of products to be disposed, recycled	Negative
		Increased fuel for transportation (towards disposal or recycling)	Negative

6. Concluding Remarks

The present work offers a cause–effect perspective on the Industry 4.0 technologies applied to manufacturing and support activities by analyzing their effect on flows directly linked to environmental sustainability.

The division of scenarios enabled us to capture in a more specific way the needs and requirements that will be faced, as well as the opportunities that arise through the different explored situations filtered by the Industry 4.0 elements and temporal and stage considerations.

Accordingly, the different degrees of implementation were examined when comparing scenarios 1 and 2. The different degrees of commitment to SD principles were examined when comparing scenarios 2 and 3. A temporal prognostic was present in scenario 4, which included two opposite trends.

The trends of the environmental sustainability impacts were stage-dependent, as observed by the comparison of scenarios 1 and 2. Whereas the trend was shown to be negative at the deployment stage, the impact during operation was expected to be positive.

The convergence of Industry 4.0 technologies towards the SDGs platform is possible but requires supportive innovation and policies. When integrated with the SDGs, Industry 4.0 is expected to drive opportunities for proactive responses, but the real integration will only occur through the use of a well-established eco-innovation platform to ensure environmental performance. The results indicate that the emerging functionalities offer a range of opportunities for environmental sustainability when adequately planned.

On the other hand, the long-term scenario of Industry 4.0 is closely dependent on societal reactions as well as on public policies, legal frameworks, and homogeneous dissemination. Heterogeneity among

the nations adopting Industry 4.0 as well as among companies with different levels of digitalized infrastructure could create niches of inequality and non-sustainability patterns.

The transparent exchange of information for consumers is a key factor in allowing responsible consumption, since this new phase places the consumer in an empowered role, which will be risky without the awareness of environmental concerns.

However, a clarification must be made. Although the flows selected to address environmental sustainability are relevant and already adopted elsewhere, it is worth noting that sustainability is an extensive concept [50]. The estimation of the flow trend when an activity is imposed is relatively straightforward. Nevertheless, an activity that is supposed to entail a positive effect on a specific flow will also depend on the total production quantity. If the total production increases, the total flows will increase, and the positive trend due to the technological contribution will be canceled. The same flows, expressed as ratios or flow intensities (intensive parameters), may show a positive trend, but they could not reflect the real global sustainability trend (an extensive concept). We tried to take this concept into consideration when examining the long-term scenario (scenario 4, both tendencies).

Although a quantitative assessment of the impact is beyond the scope of this work, it is important to highlight that environmental impact depends on the amount of total consumption of biophysical resources. According to Ehrlich and Holdren [84], the impacts are divided into three sections: population, level of consumption (affluence) and impact per unit of resource (related to technology). The concept can be expressed as environmental impact = f (population, affluence, technology).

Our approach is related to the third term and found evidence of a predominance of positive impacts in qualitative terms.

For a quantitative assessment of the environmental impact due to the effect of Industry 4.0 technologies, other methodologies should be used, such as life cycle assessment, material intensity [85] or energy accounting [54]. The adoption of these methodologies would require the definition of a scope and temporal frame that it is beyond the objective of our work.

The topic is not exhausted due to its complexity and its relevance for future generations. Scenario-based studies could contribute to helping policy makers to anticipate the nature of impacts as a consequence of the reshaping that Industry 4.0 will cause to production systems.

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