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Support of Advanced Technologies in Supply Chain Processes and Sustainability Impact

Susana Garrido Azevedo [1], Carina M. O. Pimentel [2], Anabela C. Alves [3] and João C. O. Matias [2,*]

[1] CeBER R&D Center, Faculty of Economics, University of Coimbra, Av Dias da Silva 165, 3004-512 Coimbra, Portugal; garrido.susana@fe.uc.pt
[2] GOVCOPP R&D Center, Department of Economics, Management, Industrial Engineering and Tourism (DEGEIT), University of Aveiro, 3810-193 Aveiro, Portugal; carina.pimentel@ua.pt
[3] ALGORITMI R&D Center, Department of Production and Systems, School of Engineering, University of Minho, 4800-058 Guimarães, Portugal; anabela@dps.uminho.pt
* Correspondence: jmatias@ua.pt; Tel.: +351-234-370-361 (ext. 23623)

Abstract: This paper aims to present a study of the type of advanced technologies used across manufacturing supply chains in supporting the main processes of the supply chain operations reference model (SCOR). It also intends to identify a set of sustainable performance indicators (environmental, economic, and social) suitable to evaluate a supply chain 4.0 (SC4.0). To attain this objective, based on the literature review, a conceptual model is proposed. The multiple case study is used with a cross-case comparison to identify the type of advanced technologies more commonly used in SC4.0, and the performance indicators more suitable for assessing a SC4.0 sustainability performance. A sample of ten case studies was considered with companies belonging to different manufacturing SCs, from different countries, and belonging to different echelons. Main findings revealed that the level of adoption of advanced technologies in the Supply Chain SCOR processes varies amongst the case studies. Some technologies are quite commonly used among the several SCOR processes and companies while others are seldom applied. Some indicators were also identified that are regarded as very or extremely suitable to evaluate the sustainability performance of a SC4.0. The main contribution of this research to the body of knowledge is the empirical insights on the SC4.0 field and on Supply Chain Sustainability performance measurement. The results provide guidelines for the selection of advanced technologies to support SC processes and for the design of sustainable SC4.0 performance measurement systems.

Keywords: Supply Chain 4.0; sustainability; SCOR model; manufacturing supply chain; advanced technologies; case study; cross-country comparison

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1. Introduction

The supply chain is fundamental to connect suppliers, producers and clients. It works like the arteries and veins that transport the blood to and from all cells in the human body. Currently, supply chains are highly complex enlarged networks that could start in one point of the planet and finish in another. This is only possible due to the available technologies, some provided by the Industry 4.0 concept [1]. Such supply chains have impact on the planet's sustainability, so it is mandatory that their operations become sustainable.

The industry 4.0 (I4.0) technologies as a support to the sustainability of supply chains have recently gained importance due to delivering sustainable outputs and reducing man–machine interaction, if some barriers (e.g., ineffective performance framework) are overcome [2]. Specifically, these outputs are achieved by focusing on cyber physical systems (CPS) to create sustainable smart factories in future [3]. However, the digital transformation under Industry 4.0 relies on the implementation and integration of a variety of simple to advanced Information, Digital, and Operation Technologies (IDOT) such as industrial sensors, industrial controllers, Automated Guided Vehicles (AGV), robots, Augmented and Virtual Reality (AVR), data analytics, cloud computing, Internet of Services (IoS), High-Performance Computing-powered, Computer-Aided Design and Manufacturing (HPCCADM), and Artificial Intelligence (AI) [4,5]. Despite that many of these enabling IDOTs of Industry 4.0 have been available during the past four decades [6], only recently have they reached a maturity level in terms of interoperability [7].

The concept of sustainability in SC has also gained also relevance during recent decades [8], motivated by the continuous growth in competition at global level which has led to a shift in sustainability practices in order to remain stable [9]. Sustainability concerns should start from product idea generation until delivery of final product to the final user [10]. To support this, several researchers working on Sustainable Supply Chain Management (SSCM) have proposed frameworks for improving the SSCM implementation rate [11,12]. However, it is important to notice that at present industry is switching quickly towards digitalization and it has become difficult for organizations to adopt SSCM effectively using traditional SC practices [13]. According to Christopher [14] and Wu et al. [15] the goal of a SC is the management of upstream and downstream relationships in order to create value at less cost for all stakeholders. The use of advanced technologies represents an important contribution to achieve this purpose. The enhanced automation and advanced technologies used help practitioners to develop strategies to face these challenges and to achieve effective sustainability in their existing SC systems [16]. Ghadimi et al. [17] argue that the literature strongly demands innovative solution measures that help organizations to easily adopt SSCM according to a changing industry environment, which includes industry 4.0 [18].

The research on the economic, environmental, and social sustainability impact of the fourth industrial revolution is still a recent topic requiring further investigation. Digitalization of SCs will result in output optimization through removing various types of waste and non-value-added activities [19]. A SC can also be considered as adopting a sustainable behavior if sustainability concerns are identified at each level [20]. For this identification, the availability of a performance measurement system formed by economic, environmental and social indicators [21] is very important to assess this kind of information.

Many studies [22,23] have pointed to industry 4.0 and sustainability as the future of organizations in achieving competitiveness [4]. In the new context of SC digitalization, where sustainability is also a concern, it is important to identify a set of suitable performance indicators for assessing the economic, environmental and social sustainability of SCs. In this process, the SCOR model developed by the Supply Chain Council makes an important contribution since it is a process reference model that serves as a diagnostic tool for supply chain management in general and for assessing metrics, best practices, and technology in particular. It is focused on Plan, Make, Source, and Deliver as the stages of the supply chain [24,25].

Attending to this contextualization, it is important to know the type of advanced technology used in supporting a set of important manufacturing SC processes, particularly, what stages of the SCOR model these technologies are supporting. It is important also to recognize which performance indicators are best suited to assess SC4.0's impact on sustainability. Therefore, the main objective of this paper is to study the type of advanced technology used across manufacturing supply chains in different countries that support the main processes of the SCOR model. It also intends to identify the performance indicators most suitable for assessing SC4.0 performance in terms of sustainability. Through a multiple case study, the authors contribute to knowledge of which advanced technologies have a higher level of implementation and at which stage of the SCOR model such technologies are being implemented. Moreover, the key performance indicators related to sustainability of SC4.0 are identified.

The paper is structured in seven sections. Section 2 provides a theoretical background to the SCOR model, supply chain sustainability performance and the digitalization of SCs. Section 3 presents the conceptual model developed in this research attending to the literature review. In Section 4, the research methodology and methods are explained; after that, in Section 5 the analysis and discussion of the results of the research are explored, grounded in the literature and the achieved results. Section 6 presents the managerial implications of the results obtained. The last section is Section 7, where the main conclusions of this study are presented, as well as future research.

2. Background

2.1. SCOR Model

In process-oriented SC, a set of proposed models exists and includes descriptive and normative models (DNM) [26], Global Supply Chain Forum framework (GSCF) [27], Value Reference Model (VRM) [28], Sustainable Balanced Scorecard (SBS) [29], Process Classification Framework (PCF) [30], and the SCOR model [31].

Specifically, the SCOR model is considered by academics as a reference in the SCM field [32] for the design and enhancement of SCs [33]. This model provides a common setting for determining, unifying, and accomplishing SC processes [31], illustrating SC activities as a series of interconnecting inter-organizational processes, conventionally used in benchmarking studies [32]. This model considers the following five main processes as strategic in analyzing any topic in SCs: Plan, Source, Make, Deliver and Return, Table 1.

Table 1. Main Processes of supply chain operations reference (SCOR) Model [34].

SCOR Processes	Characterization
Plan	Balances the demand and supply to meet the sourcing, manufacturing and delivering requirements.
Source	Includes the procurement activities to acquire goods/services aligning planned and actual demand.
Make	Related to the transformation of products and services to meet planned and actual orders.
Deliver	Comprises the fulfilment of customers' demand as requested in the planned and actual orders.
Return	Is associated with all reverse movements of goods and services from customers for any reason.

In this study, the SCOR model is used to explore the advanced technologies used across its five main processes: Plan, Source, Make, Deliver and Return because of the potentials and advantages pointed out above.

2.2. Supply Chain Sustainability Performance Dimensions

This section, grounded in the literature review, aims to review a set of performance indicators to analyze the impact of using advanced technologies, in supporting SC processes, on their sustainability.

Neely et al. [35] have defined a performance measure as "a metric used to quantify the efficiency and/or effectiveness of an action". Saisana and Tarantola [36] have defined indicators as "pieces of information that summarize the characteristics of a system or highlight what is happening in a dynamic system" to assess the current state of the system. There are different ways of categorizing indicators such as quantitative and qualitative [37], financial and non-financial [38], absolute and relative [39], or based on their hierarchical focus (strategic, tactical, operational levels) [40].

The sustainability impacts of Industry 4.0 deserve the attention of researchers considering that the previous industrial revolutions resulted in dramatic and somewhat unexpected economic, environmental, and social changes. Despite being at its beginning, the consequences of Industry 4.0 and digital SCs on triple bottom line sustainability (economic, social, and environmental) are expected to be substantial [41]. Moreover, sustainability metrics are directly impacted by technologies' operationalization in processes [42], consequently influencing directly the KPI (Key Performance Indicators) metrics [43].

Sustainability has a rich literature, and academia has made a significant contribution to the conceptualization of its three dimensions: environmental, economic, and social [44]. Environmental sustainability is related to the efforts made to preserve and protect natural resources [45], maintaining the earth's environmental system's equilibrium, the balance of natural resource consumption and replenishment, and ecological integrity [46]. In this context, environmental sustainability performance measures are concerned mainly with the environment, but preserving long-term economic growth and the social resources. Thus, economic growth should not ignore the balance in natural resources, ecosystems, social welfare, and distribution of wealth [47]. Environmental sustainability performance measures essentially expand our common perception of human activity. This makes the connection with the ecological concept of interdependence more clearly, thus defining the limits of use of sustainability to match the overlap of human activities with ecosystem functioning support [48]. Social sustainability of an organization is the way in which it manages its responsibilities towards its social and human capital [49], being concerned with the creation of healthy and livable communities where everyone is protected from discrimination and has access to universal human rights and basic amenities such as security or healthcare [50]. The economic sustainability of an organization outlines the distribution and flow of financial resources among the organization's stakeholders and its impact on the environment and the society [51]. The economic dimension of sustainability performance is quantitative in nature, being focused on the efficient use of resources to achieve a return on investment.

In contrast, an increased rate of production, thanks to industrial automation, would be associated with higher resource and energy consumption as well as an increase in pollution levels [52,53]. This is why Ohno, the Toyota Production System mentor, considered overproduction the worst kind of waste and created the concept of JIT (Just-in-Time) production [54]. Having these roots, Lean Production [55] has been synergistically associated with sustainability, under the designation of Lean-Green [56–58]. Such a link has also been extended to SC [59–61].

Thinking of the social consequences of digital transformation and the reorganization of the industry, experts believe that digitalization and the emergence of labor-saving technologies will eliminate most lower-skilled jobs while creating countless job opportunities in various areas such as automation engineering, control systems design, machine learning, and software engineering [62].

Organizations are responsible for their business activities. These activities affect the environment, society, and economy not only in their own business but also for their SC partners [63].

In terms of sustainability performance measurement, a balanced set of indicators that covers the three dimensions of sustainability is required (social, economic and environmental). Some environmental sustainability indicators have been used, for example, rate of hazardous waste, amount of water consumed per year in industrial processes, or the amount of energy used per year [64]. Several sustainability indicators belonging to each of the three dimensions of sustainability, used in many works, come from a set of standards and guidelines. According to Saeed and Kersten [65] the three SC sustainability-related guidelines that directly address the three dimensions of sustainability are: (i) the Global Reporting Initiative (GRI); (ii) the OECD sustainability indicators and (iii) the Institution of Chemical Engineers (IChemE). For example, Abreu et al. [66] proposed an indicator to, jointly, measure sustainability dimensions grounded on the GRI indicators and Overall Equipment of Effectiveness (OEE), in order to measure operational performance.

In the literature, there are several performance measures that have been used to evaluate the impact of advanced technologies on organizational performance. According to Kamble et al. [67] Industry 4.0 facilitates achieving a high level of process integration, leading to improvement in organizational and SC performance on all three sustainability dimensions. In the economic dimension, the use of advanced technologies contributes strongly to value creation, manufacturing flexibility, and product customization, leading to increased customer satisfaction [5].

The automation and digitalization features of SC 4.0 drive the manufacturing organizations towards reduced lead times, lower manufacturing costs, and higher quality [68]. In the environmental dimension, the real-time information gathered from different value chain partners helps the organizations allocate their manufacturing resources, such as materials, energy, water, and products, efficiently [41]. The use of advanced technologies also supports the reduction of greenhouse gas emissions [69], energy consumption [70], and inventory levels of raw material; reductions in fuel consumption as a result of improved transport and logistics planning; and use of advanced tracking and monitoring systems [71].

On the social dimension, it offers abundant opportunities for employees to learn new technologies, thereby improving morale and motivation [70], offering an improved work environment and safe working conditions for employees [67].

In this study a hierarchical approach was used considering firstly the three dimensions of sustainability (environmental, social, and economic), then a set of performance measures associated with each dimension, and finally several performance indicators that reflect each performance measure, Table 2.

Table 2. Performance Measurement System Proposal for Sustainability Assessment.

Sustainability Dimension	Performance Measures	Performance Indicators	Authors
Environmental Dimension	Energy Efficiency	Total annual renewable energy consumption of an organization.	[52,53,65,72,73]
	Water management	Total annual volume of water recycled/reused by organization.	[39,65,73–75]
	Emissions	Total annual amount of direct GHGs emissions by an organization. Total annual amount of ozone-depleting substances by an organization.	[39,72,73]
	Waste management	Waste reduction. Total annual amount of hazardous waste generated by an organization	[72,73,76,77]
	Supplier assessment	Percentage of suppliers subject to sustainability assessment. Percentage of local/national/provincial suppliers of an organization.	[39,72,73].
Social Dimension	Human resources	Total annual number of employees in an organization. Total annual number of female employees in an organization. Total number of employees' turnover.	[11,39,75,78,79]
	Training and education	Total number of employees given training in an organization.	[74,80]
	Consumer issues	Total number of incidents of consumer complaints.	[73,74]
Economic Dimension	Income distribution	Total annual amount of wages and benefits given to employees by an organization. Total annual operating costs of an organization.	[11,39,78,79]
	Sustainability expenditures	Percentage of procurement budget spent on local suppliers. Total annual sustainability expenditure by an organization.	[39,72]
	Stability and profitability	Total annual sales/revenues of the organization.	[73,77].

2.3. *Digitalization of Supply Chains—SC4.0*

Supply chains are increasingly more complex, expensive, inexact, and fragile. To deal successfully with the increasing challenges, SCs must become smarter [81] with new interconnected business systems which extend from isolated, local, and single-company applications to the supply chain. The smart SC uses many advanced technologies and systems, such as Internet of things (IoT), smart machines, intelligent infrastructure, intelligent decision-making, and efficient and responsive processes [15] to establish a large-scale intelligent infrastructure for merging data, information, physical objects, products, and business processes [82].

The smart SC, also known as SC4.0, offers a vertical and horizontal integrated supply network within which all the value functions such as smart suppliers, connected customers, smart factories, production machinery, smart products, and intelligent materials interact and communicate with each other in real-time and at the global scale [15,83,84]. The application of all these advanced technologies such as IoT, big data analytics, or cloud data leads to the decentralization of production that enables machines, human resources, materials, and process controllers to intercommunicate in real-time as naturally as in a social network [85]. Technological integration in the SC has also led to innovative systems such as, SMART containers, SMART warehousing, SMART ports, SMART shelves, and SMART manufacturing [86]. All these innovations associated with the digitalization of the SC contribute to an increase in the amount of communication efficiency, transparency, surveillance, and control, and, consequently, to minimize downtime, waste, defects, and risk across production processes [87,88].

These technologies enable a smoother integration of Lean Production, Logistics and SC that allows a better business performance by focusing on waste in the entire value stream [76,89–91]. Moreover, according to Chaopaisarn and Woschank [92] the adoption of advanced technologies in SCs contributes not only to waste elimination, but also to increase SCs' agility by allowing their members a quicker response to market changes and technologies through configurable SC cloud networks.

According to Wu et al. [15] a Smart SC has some distinctive characteristics compared to the traditional ones such as: (i) information is overwhelmingly machine-generated; (ii) the entire SC, comprising business entities and assets, IT systems, products, and other smart objects, are connected; (iii) large-scale optimal decisions are made to optimize performance; (iv) many of Smart SCs process flows are automated by means of machines to replace other low-efficiency resources including labor; (v) the integration of SC processes through collaboration across SC stages; and (vi) the development of new values through solutions that meet new requirements.

These characteristics are important drivers to a better collaboration and integration under the platform of Smart SCM giving rise to many advantages such as: (i) ICT enables products and production to be engineered digitally; (ii) modular simulations and techniques allow firms to decentralize and change production processes and thereby stimulate faster innovation of processes and products [93], (iii) reduction of lead time in product design and prototyping through improved SC visibility, (iv) the time benefit of increased data availability at the SC level, especially regarding time compression of innovation cycles [84], (v) SC members save costs in research and development processes and can respond to customers' specific demands [94].

Moreover, some advanced technologies can be used to obtain the most significant insights for supporting SC management [68]. The digitalization of supply chains contributes to the integration of a lot of SC functions, such as automation of warehousing, autonomous smart vehicles, human-machine interfaces, SMART logistics planning algorithms, reliable online order monitoring, real-time re-planning, real-time vendor inventory monitoring and no-touch processing, providing advantages through the process of physical flow and management of orders [93,95].

This trend in the use of advanced technologies holds new opportunities. Nevertheless, it also carries unforeseen new challenges for producing new business models and refining existing operations, thereby generating market benefits [96] such as the possibility to obtain complete information about customer demand, inventory levels, cost, pricing, location, capacity, quality and technological information, which could be shared among partners [97].

In their work, Mittal et al. [98] presented a list of 38 different technologies. These are associated with smart manufacturing and clustered into the following 11 groups: data analytics/big data; visual technology; intelligent control systems; energy saving/efficiency technology; smart products/parts/materials; cloud computing; cybersecurity; internet of things (IoT)/internet of services (IoS); cyber-physical systems (CPSs); three-dimensional printing/additive manufacturing; advanced manufacturing; and IT-based production management.

3. Conceptual Model Proposed

The use of advanced technologies is strategic in a context where better business processes are developed to support higher efficiency and faster response. In addition, dynamic complexity has overtaken the possibility of human intervention to identify and solve many system issues and, being digital, SCs can remove many of the persistent inefficiencies. As such, it is harder to achieve performance improvements through the traditional means and companies are compelled to develop newer solutions arising from technology and business-model based innovations. Furthermore, the costs of instrumentation have declined dramatically in recent years and smart devices are being deployed everywhere [99] contributing to a massive use of advanced technologies.

The Supply Chain Operations Reference (SCOR) model offers standard guidelines for companies [33] to aid in SC configuration, identification and measurement of metrics and continuous application of best practices. It is considered an analytical tool that gathers performance processes, metrics, best practices, and people into an integrated structure, being frequently used as a deductive framework to study SC topics, as mentioned by Sangari and Razmi [100].

Several authors [41,67] have argued that the digital connectedness and information development and sharing associated with digitalization may have contradictory impacts on triple bottom line sustainability. The digitalization of manufacturing and lean business processes together with deployment of smarter machines and devices may offer numerous advantages such as manufacturing productivity, resource efficiency, and waste reduction [76,89–91]. Therefore, a SC can be considered as showing a sustainable behavior if sustainability concerns are identified at each level of the SC [20], the existence of a performance measurement system formed by economic, environmental and social indicators being very important to assess this kind of information [21].

Attending to the literature review the following conceptual model is proposed in this study (Figure 1).

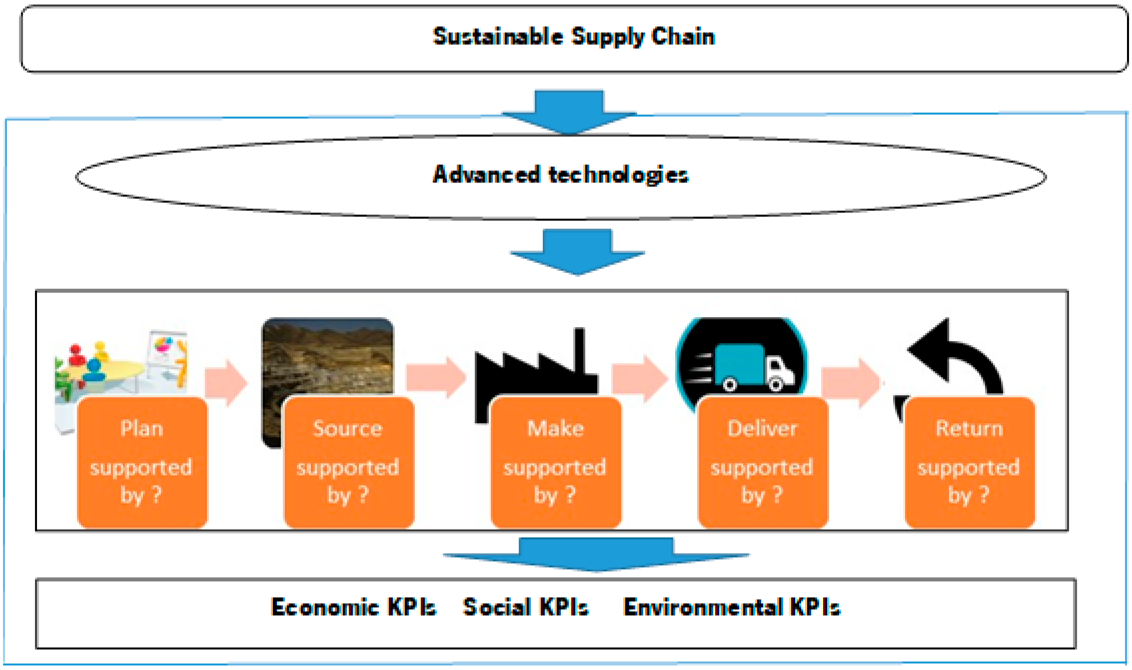

Figure 1. Conceptual model developed in this research.

4. Research Methodology

In this study, a qualitative methodology supported by case studies is used. According to Perry [101], Rowley [102] and Yin [103], a case-study approach is suitable when the frontiers of a phenomenon are not only unclear but there is no control over behavioral events. In this research, the boundaries (advanced technologies used in supporting the SCOR processes of manufacturing SCs 4.0 and the sustainable performance indicators more suitable to evaluate this) are still relatively vague.

Case studies are usually carried out in close interaction with practitioners, and they deal with real management situations. Case studies consequently represent a methodology that is ideally suitable to generating managerially relevant knowledge [104,105]. While case studies may, and often do, use quantitative data, a key difference to other research methods is that case studies seek to study phenomena in their contexts, rather than independent of context [106]. Other advantages pointed out in the case study methodology are: (i) the examination is conducted in the context in which activity takes place [107]; (ii) variations in terms of intrinsic, instrumental and collective approaches to case studies allow for both quantitative and qualitative analyses of the data [108]; (iii) it allows researchers to learn from the case studies [108]; (iv) it provides a detailed qualitative description of a phenomenon [107,108]; (v) case studies can be accomplished conductively and inductively [109]. Moreover, by using multiple cases each case's conclusions can be used as information contributing to the whole study [110], helping to raise the level of confidence and robustness [107,111].

Second, case studies are frequently used in close interaction with practitioners, and they deal with real management situations. Hence, case studies represent a methodology that is ideally suited to creating organizationally relevant knowledge [104,105].

Case studies can be exploratory, descriptive, or explanatory. Since little empirical evidence exists, it is too early to develop testable hypotheses, and consequently the research is exploratory in nature [103]. Moreover, at this early stage of research it is better to cover the different tiers within a SC and the realities of different countries. To this end, ten cases from the manufacturing sector were analyzed as a way of identifying the advanced technologies they use in supporting the different SCOR processes and to gain professionals' perception about the suitability of a set of performance indicators to assess the impact of those technologies on the sustainability performance of SC 4.0.

According to Gibbert et al. [112], there are numerous criteria to assess the rigor of case studies. These criteria depend on the preferred model of science chosen. The model used in this article lies within the positivist tradition [112,113]. In the positivist tradition, four criteria are considered to assess the rigor of case studies: internal validity, construct validity, external validity, and reliability [114]. In a case study methodology, the internal validity can be attained by proposing a conceptual model explicitly derived from literature [103] which should demonstrate the relationships between the research variables. As can be seen above, in Section 3 a conceptual model suggesting the relationships between the research variables is proposed.

The construct validity denotes the quality of the operationalization of the relevant concepts and needs to be considered during the data collection phase. As such, construct validity refers to the extent to which a study investigates what it claims to investigate [115]. In order to enhance construct validity in case studies, researchers should establish a clear chain of evidence to allow readers to reconstruct how the researcher went from the initial research questions to the final conclusions [103]. The research design of this study is presented in the next section.

External validity, or generalizability, is grounded in the acceptance that theories must be shown to account for phenomena not only in the setting in which they are studied, but also in other settings [116,117]. Knowing that neither single nor multiple case studies allow for statistical generalization inferring conclusions about a population [103,118,119], this does not mean, however, that case studies are devoid of the possibility of generalization. There are two types of generalization: statistical generalization and analytical generalization. In this study, statistical generalization is not possible to attain but analytical generalization is. Analytical generalization is different from statistical generalization in that it refers to the generalization from empirical observations to theory, rather than to a population [103]. How, then, can case studies allow for analytical generalization? Regarding this, Eisenhardt [120] argues that case studies can be a starting point for theory development and suggests that a cross-case analysis involving four to 10 case studies may provide a good basis for analytical generalization. In this study a cross case analysis is performed using

10 case studies from different manufacturing SCs and countries which makes it possible to state that external validity is contemplated in this research. This option is also justified because according to Rosenzweig and Singh [121] SC environmental behavior may differ from country to country which could influence the type of practices that may be adopted.

In this study, convenience sampling was used. According to Zhi [122] convenience sampling is a type of nonprobability or nonrandom sampling where members of the target population that meet certain practical criteria are selected. Some examples of criteria used are easy accessibility, geographical proximity, availability at a given time, or the willingness to participate in the study. In this study, the two criteria used to choose the case studies were easy accessibility and willingness to participate in the study. Ten case studies formed by companies belonging to different type of manufacturing SCs from different countries (Portugal, Pakistan, USA, Singapore, Brazil, and China), belonging to different echelons (focal company, first-tier supplier and second-tier supplier), with different levels of expertise in Supply Chain Management 4.0 projects and ranging from large companies to SMEs, were chosen.

The case-study method has three distinct stages: design, data collection and analysis. The final stage is an analysis of the individual case studies, allowing "cross-case" reports to be written [103]. This research is based on the qualitative data analysis method developed by Miles and Huberman [123], which consists of data collection, reduction, display, and conclusion testing. This same methodology can be found in Bryman and Burgess [124].

4.1. Research Design and Data Collection

The design of this research is illustrated in Figure 2. Firstly, a literature review of advanced technologies supporting the digitalization of SCs, the SCOR Model and the performance of SCs in terms of sustainability was performed. From the literature, the research questions were formulated and an adequate methodology to achieve the research objective chosen. The case study methodology was used, based on virtual interviews with managers from manufacturing companies located in different countries. To collect data, an interview protocol was developed. The protocol was pre-tested with a senior manager of an automotive company. The pre-test consisted of first mailing the protocol and then interviewing this individual by phone and in person regarding the appropriateness and clarity of the questions. The individual provided written and verbal comments which helped to validate the protocol. Subsequently, a few structural changes were made to the protocol. Based on the analysis of results some conclusions were drawn and the practical implications of this study to professionals from manufacturing companies belonging to SC were suggested.

The data collection was carried out through virtual (by email) semi-structured interviews, launched with professionals from manufacturing companies around the world. Multiple interviews were used to provide a broader view of the variables under study. Two set of variables were assessed: (i) advanced technologies adopted by companies belonging to different SCs in supporting the different SCOR processes; and (ii) Performance indicators to assess the level of performance of SC4.0 in terms of sustainability, considering the three dimensions of sustainability: economic, social and environmental. The same structured interview protocol (Appendix A) was used at each session to avoid interviewers' bias. In all cases, the company names are withheld in accordance with the general request for confidentiality.

4.2. Data Analysis

The data collected in the ten case studies was analyzed by using a cross-case analysis. Cross-case analysis allows the identification of leading variables among all case studies. From the analysis, it is possible to identify the advanced technologies used by the case study companies belonging to different SCs by SCOR process, as well as the perception of the interviewees on the suitability of a set of indicators to assess the sustainability of SC 4.0. The data was analyzed by using descriptive statistics.

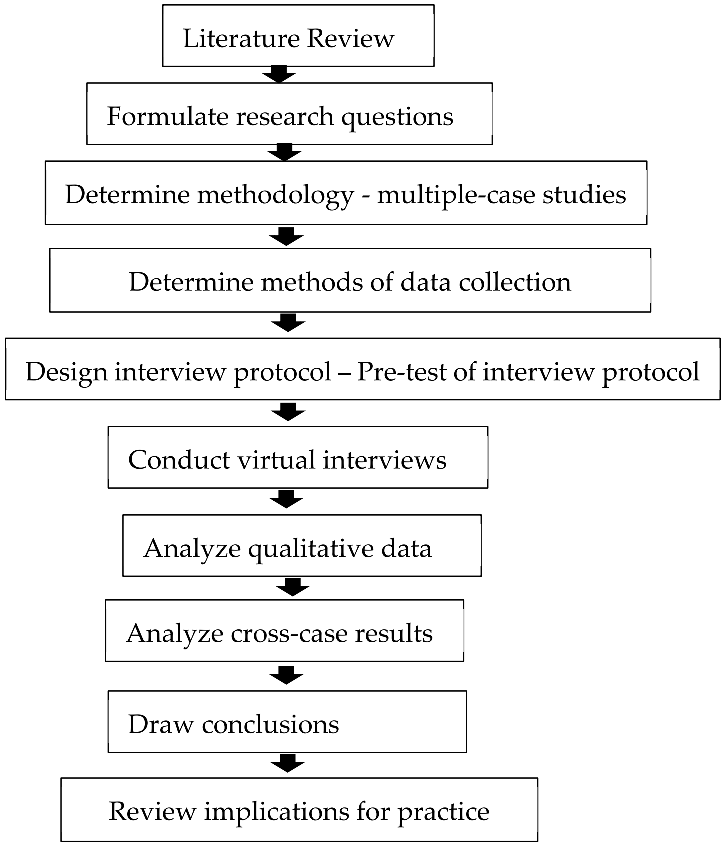

Figure 2. Research Design of the study developed in this paper.

5. Analysis and Discussion of Results

This section begins with a presentation of the case studies profile. Then, the advanced technologies used by the case studies to support their SCOR processes are also presented. Finally, the KPI to assess the level of sustainability of a SC4.0 are identified.

5.1. Case Studies Profile

The companies belonging to different SCs that agreed to collaborate with this study are from different sectors, have different sizes, operate in different countries, and are positioned in different tiers of the SC. The respondents that collaborated with this study also have different profiles. As can be seen in Table 3 the research companies belong to different SCs: refrigerator manufacturing, textile and clothing, biomass energy, metals and mining, production of food and beverages for catering/retail for aviation, automotive, cork industry and electronics manufacturing services (EMS). Most of them are large companies and operate in different continents and countries: four in Portugal and the others in Pakistan, USA, Singapore, Brazil and China. They are also part of different SC tiers, first-tier supplier being, however, the most represented category. Regarding those interviewed, most of them are working in production or operations management as senior managers (Table 3).

Table 3. Case Studies Profile.

	Company' Position in the Supply Chain	Job Level	Respondent Job Responsibilities	Number of Years in the Job Title	Respondent Job Title	Country Where the Company Operates	Number of Employees	Company Level of Expertise in SCM 4.0 Projects	Primary Product(s)	Company Supply Chain
Case 1	Focal company	Middle Manager	Responsible to meet production targets	2	Production Engineer	Pakistan	4000	Intermediate	Refrigerators	Refrigerator Manufacturing
Case 2	First-tier supplier	Middle Manager	Continuous Improvement and Engineering Design	1	CI & Design Engineering Manager	US	900	Intermediate	Athletic Apparel	Textile and Clothing
Case 3	First-tier supplier Second-tier supplier	Middle Manager	Industrialization of new Projects	2	Industrial Program Leader	Portugal	+/- 600	Intermediate	Exhausts/Seating/ Interiors	Automotive
Case 4	Focal company	Top Manager	General management	6	General manager	Portugal	17	Low	Torrefied biomass pellets	Biomass energy
Case 5	Third tier supplier	Top Manager	Production and warehouse	5	Senior Manufacturing Manager	Singapore	150	Advanced	Copper and Copper alloys	Metals and Mining
Case 6	First-tier supplier	Top Manager		Less than 1	Head of Retail Operational Excellence	Brazil	43,000	Intermediate	Production of Food and beverage	Catering/Retail for Aviation
Case 7	Second-tier supplier	Top Manager	Plant Operations Manager	12	Plant Manager	Portugal	600	Advanced	Wires and Cables	Automotive
Case 8	First-tier supplier	Middle Manager	Planning production	Less than 1	Plan and Production Engineer	Portugal	300	Intermediate	Cork Stoppers	Cork Industry
Case 9	Second-tier supplier	Top Manager	Main job control: Production Planning and Material Purchase	1	Production Procurement	China	1000–5000	Low	Assembly Injection Plastics	EMS Manufacturing
Case 10	First-tier supplier	Top Manager	Supply chain management	4	Head of logistics	Portugal	650	Low	Automotive parts maker	Automotive

5.2. Advanced Technologies Used by the Case Studies

In this sub-section an analysis of the advanced technologies used by the researched companies is provided. Regarding the technologies focused on in this study, Cybersecurity and the IT-based production management are the most commonly used by the researched companies. This result is expected as IT security solutions are essential for all kinds of businesses, particularly when we think of the importance of the internet and digital systems for the daily operations of companies. Following closely are Data analytics/Big Data and Energy saving/efficiency technology. Data analytics/Big Data has an important presence among the companies, which could be justified because companies more than ever must be able to handle huge amounts of data in a fast and reliable way in order to be more rigorous in the decision making process [125].

Then, with five companies using them, come Intelligent control systems, Smart products/parts/materials, Cloud computing, Three-dimensional (3D) printing/additive manufacturing and Advanced manufacturing, Figure 3.

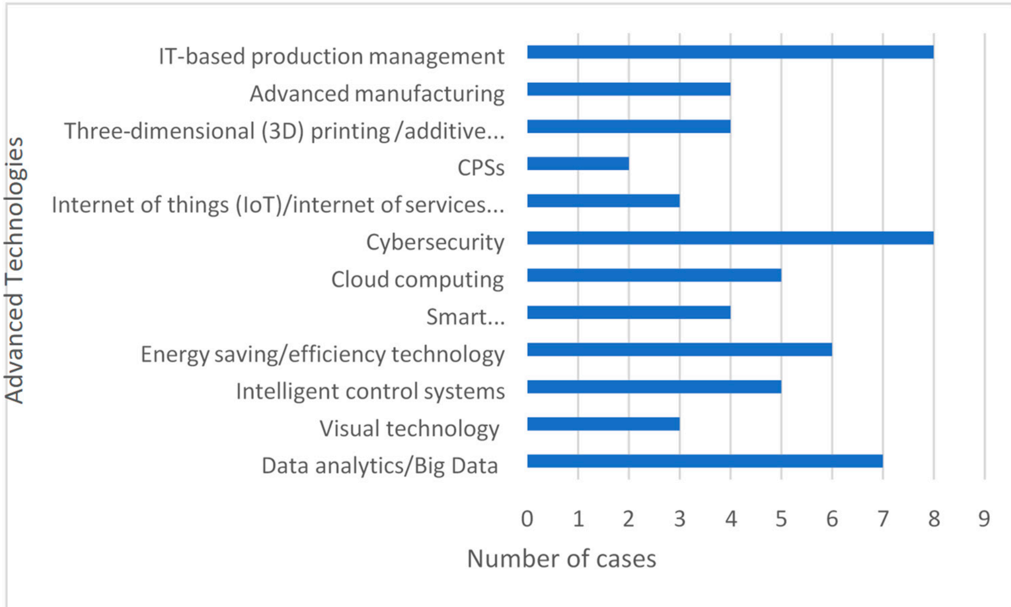

Figure 3. Advanced Technologies used by the case studies.

In Figure 4, for each case study, the total number of advanced technologies and the total number of SCOR processes supported by advanced technologies are presented. In general, there are no significant differences amongst the case studies in the number of technologies adopted, except for case 4 (Biomass energy). The result for case 4 is not expected since according to Flak [126] there are many advanced technologies identified in the ICT-BIOCHAIN project, such as ICT, Internet of Things (IoT), and Industry 4.0 technologies, that are utilized in biomass supply chains and constitute the current state-of-the-art.

The differences become higher when analyzing the total number of SCOR processes that are supported by advanced technologies.

5.3. Advanced Technologies Used to Support SCOR Processes

A cross-case analysis was performed to explore the advanced technologies used by the researched companies to support SCOR processes. Figure 5 shows which of the advanced technologies proposed by Mittal et al. [98] are used by the companies in supporting each SCOR process.

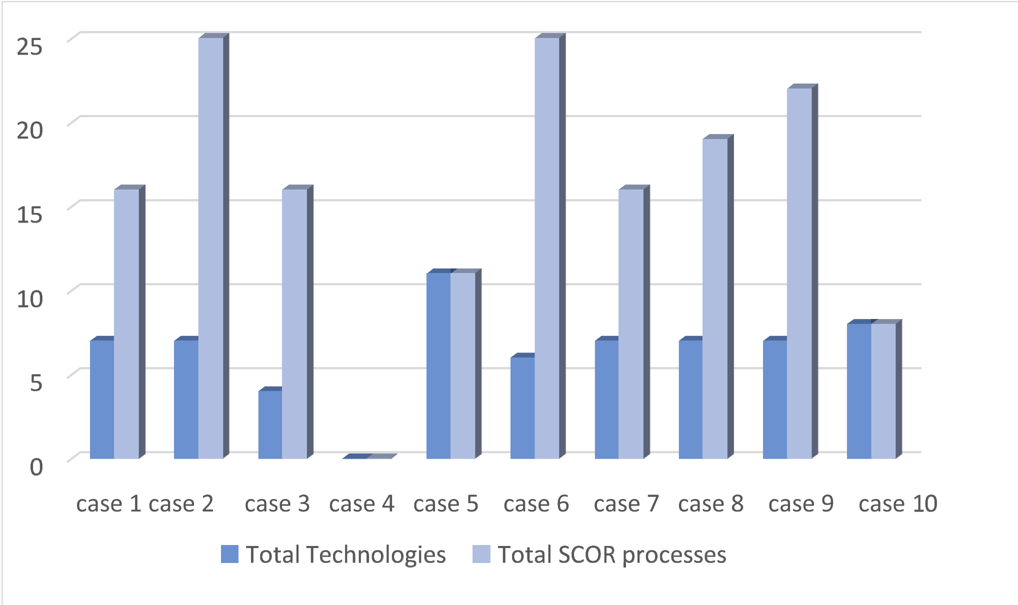

Figure 4. Number of Advanced Technologies and SCOR processes supported by case study.

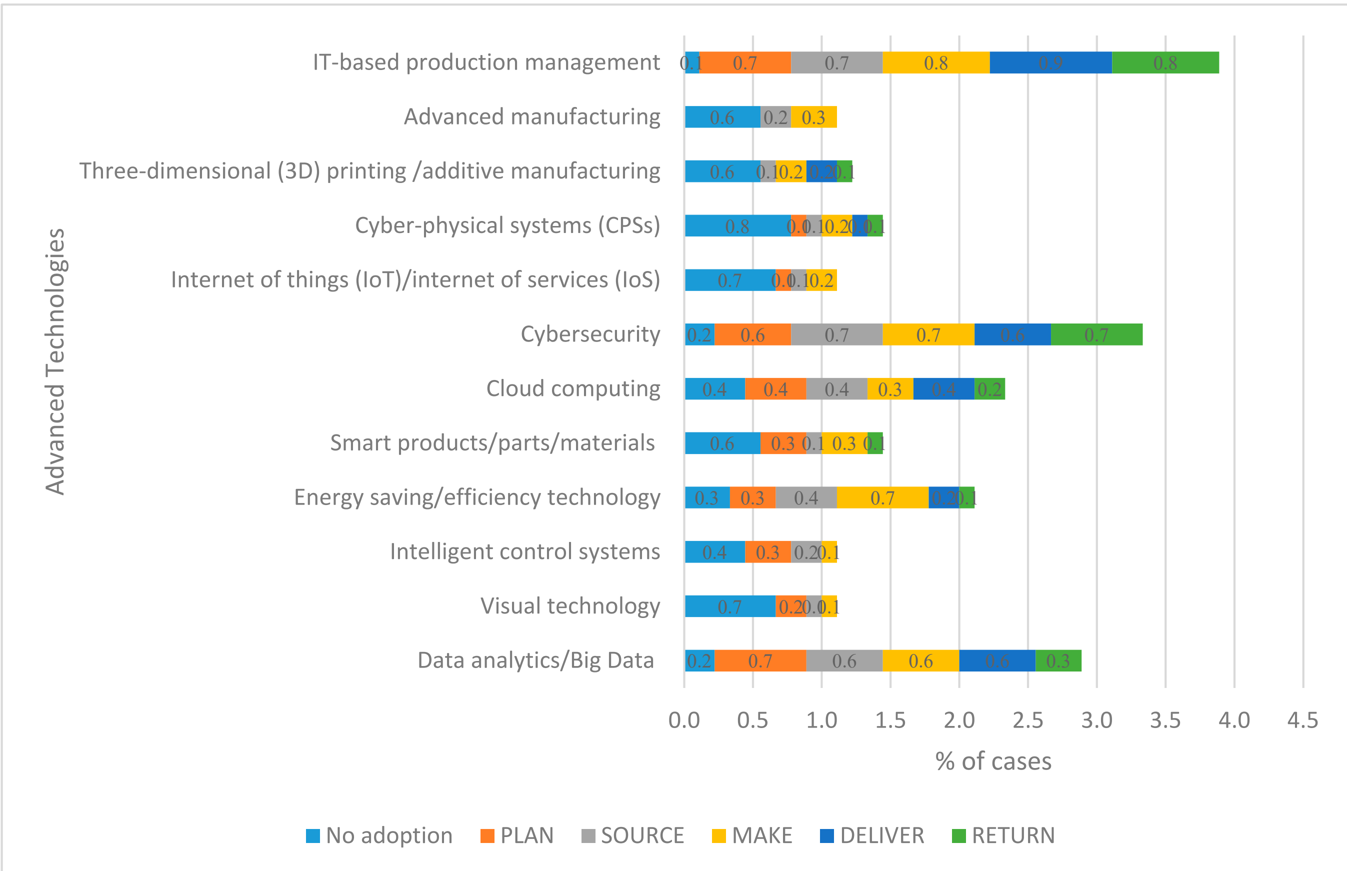

Figure 5. Advanced technologies adoption by SCOR processes (in percentage).

According to Figure 5, Data analytics/Big Data is used by three companies involved in production of food and beverages to catering/retail for aviation, cork industry and EMS manufacturing to support all the SCOR processes. This technology, however, has not been adopted by two companies from the following three manufacturing sectors: the automotive sector (exhausts/seating/interiors), the refrigerator industry and the biomass energy (torrefied biomass pellets). The SCOR processes where this technology is more commonly used are "Plan", "Source", "Make" and "Deliver".

Regarding Visual technology (e.g., augmented reality, virtual reality, and holograms), this is rarely used by sample companies. Only three of the case studies use it: one (refrigerators) uses it to support the "Plan" and "Source" processes of the SCOR model; another from the metals and mining sector uses it in the "Make" process; and finally the case which is dedicated to assembly injection plastics uses Visual technology in supporting the "Plan" process.

Attending to Intelligent control systems (use of AI techniques, such as expert systems, fuzzy logic, machine learning and neural networks), this technology is used by five case studies, two companies in the "Source" process, two in the "Plan" and one supporting the "Make". Company 6 which is dedicated to the production of food and beverages for catering/retail for aviation uses this technology in both the "Plan" and "Source" processes.

Energy saving/efficiency technology is quite commonly used by our case studies in supporting many of the SCOR model's processes. It is used by six case studies, mostly in the "Make" process. It is also interesting to see that case study 1, which is a refrigerator manufacturer, uses this technology in all the SCOR processes. Case study 3 (a producer of exhausts/seating/interiors for the automotive sector) and case study 6 (catering/retail for aviation), use energy saving/efficiency technology in supporting the same three SCOR processes: Plan, Source and Make. Cases 2, 4 and 9 do not use yet this technology.

Regarding smart products/parts/materials, these do not have so many followers as other advanced technologies considered in this study, since they are not used by five case studies. The producer of exhausts/seating/interiors, belonging to the automotive SC, is the only one that uses smart products/parts/material in three SCOR processes ("Plan", "Source" and "Make"). Another company, also from the automotive SC, which is a producer of wires and cables, uses it in the "Plan" and "Make" processes. The producer of refrigerators (case 1) uses it in the "Make" process and the producer of copper and copper alloys (case 5), belonging to the metals and mining SC, uses it in the "Return" process. Finally, the producer of automotive parts uses it in the "Plan" process.

Cloud Computing technology is used by five case studies in supporting several SCOR processes. Only company 5, which belongs to the metals and mining SC, uses it in supporting just the "Return" process. Case 2 which belongs to the textile and clothing SC, uses cloud computing in all SCOR processes. For the producer of refrigerators (case 1) and the catering/retail for aviation producer (case 6), cloud computing is used to support the processes: "Plan", "Source", "Make" and "Deliver". Companies 3, 4, 7, 8 and 10 do not use this technology.

Cybersecurity is an advanced technology used in supporting a great number of SCOR processes; more precisely it is used by five companies (cases 2, 3, 6, 8 and 9) in all SCOR processes. The copper and copper alloys producer (case 5) uses cybersecurity in the "Return" process and the producer of wires and cables (case 7) in supporting the "Make" process. The company that makes automotive parts (case 10) uses it only in the "Source" process. Only the producer of refrigerators (case 1) and the producer of torrefied biomass pellets (case 4) do not use this technology.

Surprisingly, the Internet of things (IoT)/Internet of services (IoS) is a technology used by only three research' companies, supporting a quite reduced number of SCOR processes. It is only used by the manufacturer of refrigerator (case 1) in supporting the "Make" process, the copper and copper alloys producer (case 5) in the "Source" process and the producer of wires and cables (case 7) in the "Plan" and "Make" processes.

The Cyber-physical systems (CPSs) are the least used technologies by the sample. Only the company that produces athletic apparel (case 2) uses it in all the SCOR processes. Besides, the company that belongs to the cork industry (case 8) uses it in supporting the "Make" process.

As concerns three-dimensional (3D) printing/additive manufacturing, it is observed in the sample that almost all of the companies do not use it. Only the refrigerators producer (case 1) uses this technology in supporting the "Source" process, the athletic and apparel producer (case 2) in the "Make" process, case 5 which belongs to the metals and mining SC uses the additive manufacturing in the "Return" process, and case 10 in the "Deliver" process. The assembler of injection plastics (case 9) uses it in two SCOR processes: "Make" and "Deliver".

Analyzing the advanced manufacturing technology in supporting the SCOR processes, it is used by three cases (cases 2, 7, and 8) and in the "Make" process and in the "Source" process by cases 5 and 10. All the other five companies do not use it.

Finally, IT-based production management (e.g., use of ERP, MES, CAD, and CAM) it is used by all companies in supporting the SCOR processes except company 4 that belongs to the biomass energy SC. The company from the textile and clothing SC (case 2), the two from the automotive SC (case 3 and case 7), the one from the catering/retail for aviation (case 6), that from the cork SC (case 8) and case 9 from the EMS manufacturing SC use IT-based production management in supporting all the SCOR processes. There are three companies that use this technology less: the refrigerator producer (case 1) which uses it in supporting the "Make" and "Delivery" processes, the company from the metals and mining SC (case 5) in the "Return" process and the automotive parts maker (case 10) in the "Deliver" process.

Performing the analysis by SCOR process, it can be concluded that the "Deliver" and "Return" processes are those less supported by the several alternative technologies while the "Make" process is the one in which the extent of adoption seems to be more developed.

Summing up, from this analysis it is possible to state that the level of adoption of advanced technologies to support companies' SCOR processes is quite variable. There are huge differences amongst the sample companies, meaning that they are at very different stages of development regarding the adoption of advanced technologies.

Furthermore, not all companies have incorporated all technologies. Another interesting conclusion is that some companies use a given advanced technology along the SCOR processes (this is for example the case of companies in cases 2, 3, 6, 7, 8 and 9) while others use them in a particular process. For example, case 5 uses all the advanced technologies apart from CPSs, but each technology is only used in one SCOR process. As mentioned by Zangiacomi et al. [127], this may be related to the importance of understanding on which relevant technologies to focus according to the specific business addressed and the company needs.

Attending to the sample companies there seems to be a relationship between the company size and the implementation level of advanced technologies on the SCOR processes. This same result is supported by Oliveira et al. [128] who consider company size as a determinant factor to the adoption of an innovation/new technology. Companies 10 and 8 can be considered exceptions: company 10 because it has 650 employees and has the second smaller number of SCOR processes supported by advanced technologies and company 8 because is the third company with the smaller number of employees (300) but it has a total of 19 situations where advanced technologies are supporting the total SCOR processes. This is explained in previous literature, e.g., Kagermann et al. [1], which highlighted that many SMEs are not prepared for the structural changes that Industry 4.0 will entail. However, Tortorella and Fettermann [129] argue that size should not be an impediment to the adoption of Industry 4.0 and that it is feasible in both small and larger size companies.

Furthermore, from the analysis of the sample there seems to exist a link between the level of expertise of a company and the implementation level of advanced technologies, apart from company 9 that considers that its level of expertise in SC4.0 projects is low, although it has seven technologies supporting the SCOR processes in 22 situations.

After the analysis of these results, it is possible to update the model as presented in Figure 6 attending to the most referred advanced technologies used by our sample companies.

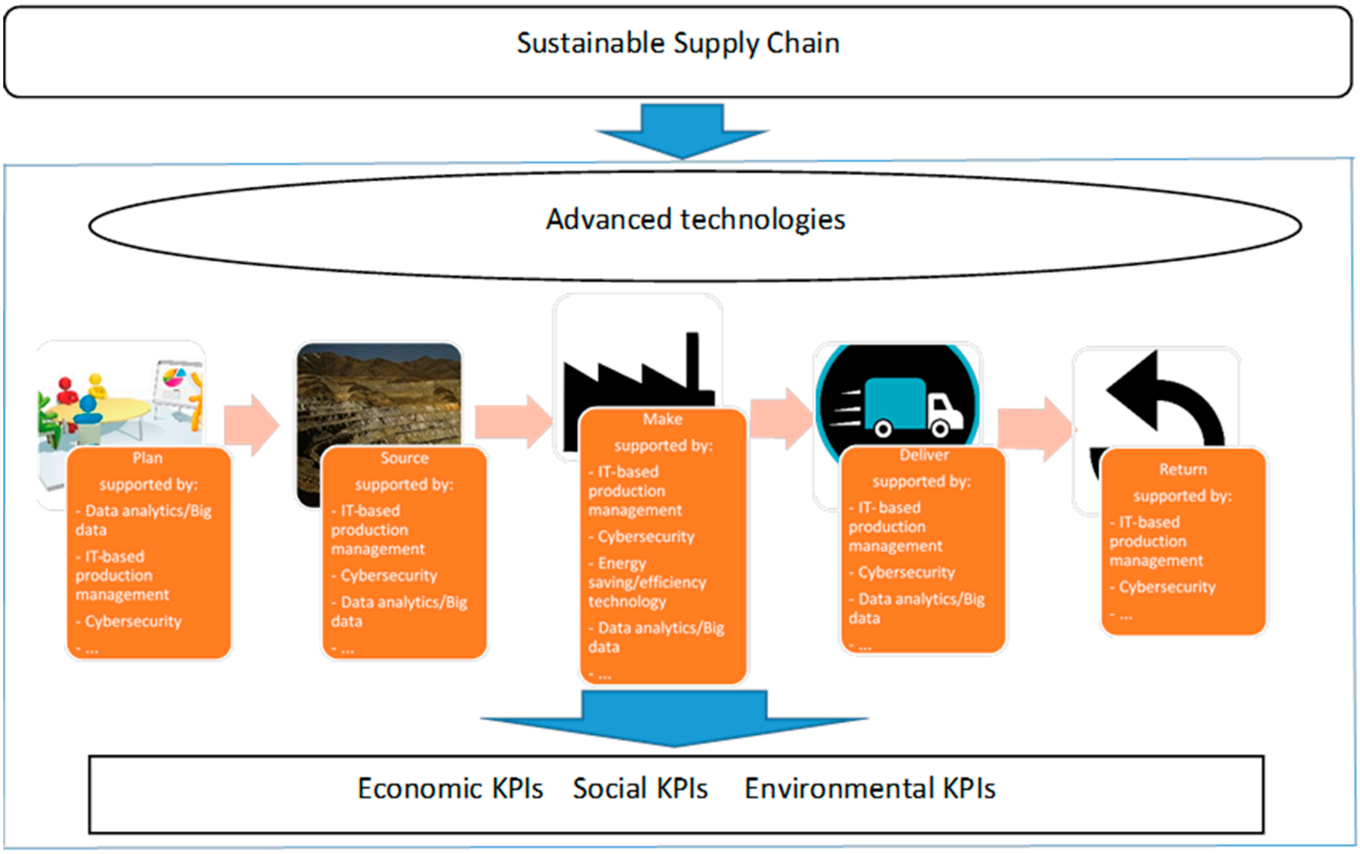

Figure 6. Conceptual model updated with the results achieved.

5.4. Key Performance Indicators to Assess the Level of Sustainability of SC4.0

The key performance indicators (KPIs) used in this study, by sustainability dimensions, are:

Economic sustainability:

EC1—"Total annual amount of wages and benefits given to employees by an organization";
EC2—"Total annual operating costs of an organization";
EC3—"Percentage of procurement budget spent on local suppliers";
EC4—"Total annual sustainability expenditure by an organization";
EC5—"Total annual sales/revenues of the organization";

Social sustainability:

S1—"Total annual number of employees in an organization";
S2—"Total annual number of female employees in an organization";
S3—"Total number of employees' turnover";
S4—"Total number of employees given training in an organization";
S5—"Total number of incidents of consumer complaints";

Environmental sustainability:

E1—"Total annual renewable energy consumption of an organization";
E2—"Total annual volume of water recycled/reused by organization";
E3—"Total annual amount of direct GHGs emissions by an organization";
E4—"Total annual amount of ozone—depleting substances by an organization";
E5—"Waste reduction";
E6—"Total annual amount of hazardous waste generated by an organization";
E7—"Percentage of supplier's subject to sustainability assessment";
E8—"Percentage of local/national/provincial suppliers of an organization".

As can be seen in the Figure 7, for the research companies the performance indicators considered as more suitable to assess the performance of a Supply Chain 4.0 in terms of economic sustainability are the following two: "Total annual operating costs of an organization" (EC2) and "Total annual sales/revenues of the organization" (EC5). Less suitable is the "Percentage of procurement budget spent on local suppliers" (EC3).

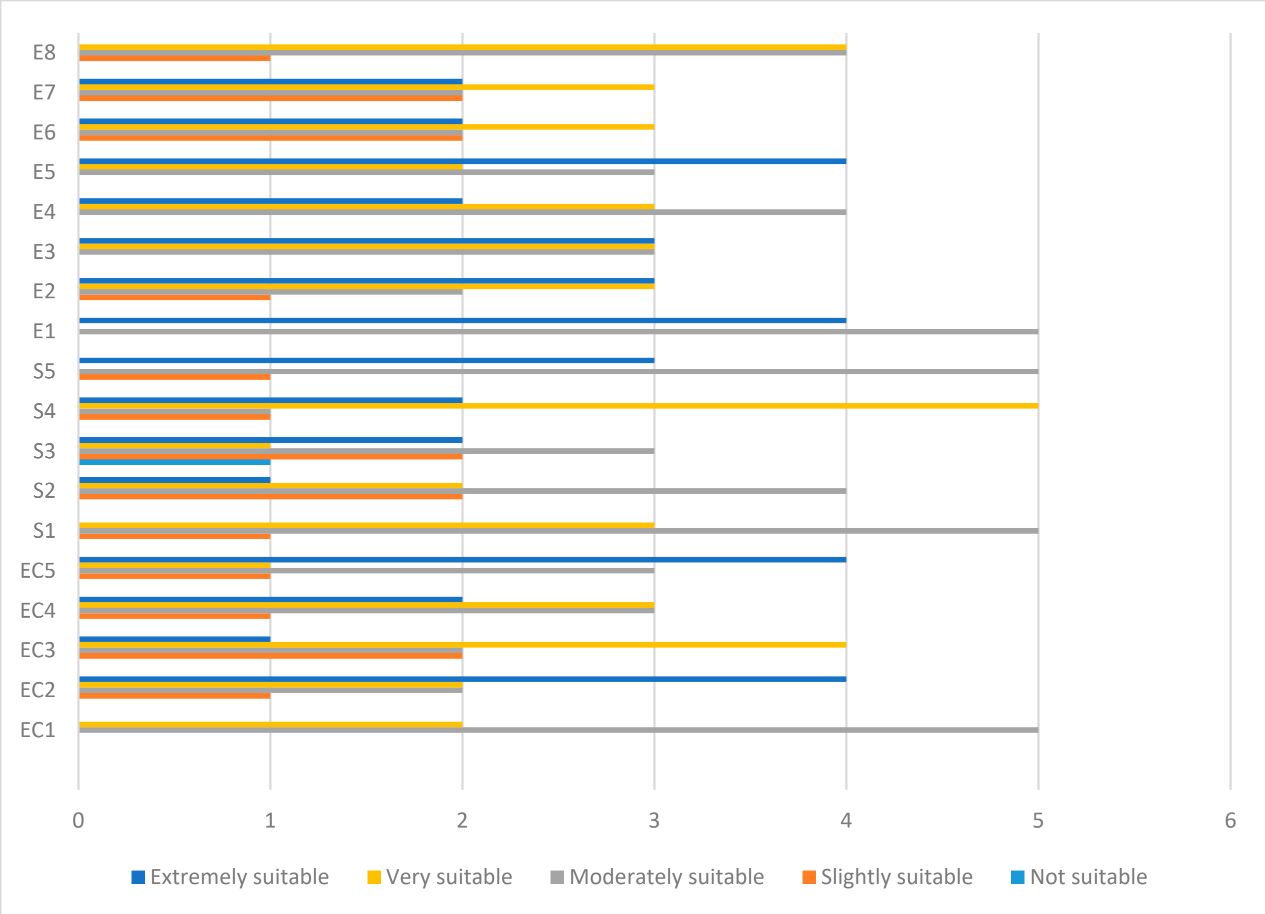

Figure 7. Key performance indicators to assess the sustainability of SC4.0.

Regarding social sustainability, the indicator identified by a higher number of companies as extremely suitable for assessing the performance of a sustainable SC 4.0 is the "Total number of incidents of consumer complaints" (S5). The indicator considered not suitable for assessing the social sustainability of SC 4.0 is the "Total number of employees' turnover" (S3), but it was only identified by one company, and therefore without much reliability.

Concerning the environmental indicators, the two identified as extremely suitable to assess the environmental sustainability of SC 4.0 by four of our sample companies are the "Total annual renewable energy consumption of an organization" (E1) and "Waste reduction" (E5). Contrary, two of the indicators were considered as slightly suitable by two sample companies: "Total annual amount of hazardous waste generated by an organization" (E6) and "Percentage of supplier's subject to sustainability assessment" (E7).

From all the indicators, there are four considered by most of the companies as moderately suitable for assessing the sustainability performance of SC 4.0.: "Total annual amount of wages and benefits given to employees by an organization" (EC1); "Total annual number of employees in an organization." (S1); "Total number of incidents of consumer complaints" (S5); and "Total annual renewable energy consumption of an organization" (E1).

6. Managerial Implications

This study represents an important contribution to professionals from industrial companies that are already, or that expect to be, part of the fourth industrial revolution giving them some insights on the advanced technologies that could be used in supporting the SCOR (Plan, Source, Make, Deliver, Return) processes and in which of them these kinds of technologies are most used.

Moreover, and based on the literature review, a set of economic, environmental, and social performance indicators are also suggested to assess the level of sustainability of a SC4.0.

This work intends to call the attention of industrial companies to the fact that they could, at the same time, use a large range of advanced technologies and implement a performance measurement system to assess their level of sustainability as member of a SC4.0.

Furthermore, the main conclusions drawn from this study, which were based on a cross-case analysis, represent an important contribution for professionals, giving them strategic information on the advanced technologies most used in the SCOR processes, which are "IT-based production management", "Cybersecurity" and "Data analytics/Big Data". If professionals from industrial companies wish to take the first steps towards the digitalization of SCOR processes they could start by implementing these technologies.

A set of environmental, social, and economic performance indicators are also identified as the most suitable to assess the sustainability of a SC4.0, which allows a SC that has implemented a set of advanced technologies to evaluate its sustainability behavior.

7. Conclusions and Future Research

As a main conclusion from our study, grounded on the 12 advanced technologies considered, it can be said that the level of adoption of SC4.0 technologies to support SCOR processes is quite low. Despite that, there are some specific advanced technologies that have a high level of implementation. This is in line with Veile et al. [130], that so far there is little experience in corporate practice with respect to a purposeful and successful Industry 4.0 implementation. Van Loon and Van Wassenhove [131] argue that only recently has industry 4.0 gained importance by reducing the interaction between man and machine. Zangiacomi et al. [127] also state that manufacturing companies are undertaking a peculiar digital transformation path, with different approaches and related level of implementation, according to their specific needs and efforts.

In relation to the suitability of the KPIs analyzed in our empirical study to assess the sustainable performance of a SC4.0, the findings show that two economic, one social and three environmental indicators stand out, when considering the number of respondents that consider them very or extremely suitable. These KPIs are "Total annual operating costs of an organization" (EC2), "Total annual sales/revenues of the organization" (EC5), "Total number of employees given training in an organization" (S4), "Total annual volume of water recycled/reused by organization" (E2), "Total annual amount of direct GHGs emissions by an organization" (E3) and "Waste reduction" (E5). The "Total annual operating costs of an organization" (EC2) is a performance indicator used by Ramadan et al. [132] to evaluate the impact of automation and digitalization of SCs on the performance of manufacturing companies. The "Total annual sales/revenues of the organization" (EC5) is considered a profitability indicator suggested by Carter and Easton [73] to assess the sustainability of a SC. The social sustainability indicator "Total number of employees given training in an organization" (S4), has been used by companies in their corporate social responsibility reports [80]. The KPI "Total annual volume of water recycled/reused by organization" (E2) and the "Total annual amount of direct GHGs emissions by an organization" (E3) are suggested by Ahi and Searcy [39] to measure performance in sustainable supply chains.

Waste reduction (E5) is an important KPI highlighted by several authors [89,90] to assess the performance reached by a SC in using advanced technologies to integrate Lean production, and Logistics.

This is not in line with the results achieved by Nara et al. [42] in which the authors could conclude that the plastic industrial sector from Brazil is more focused on the economic pillar. In a qualitative assessment focused on ecological and social indicators, Stock et al. [133] also conclude that the "Quantity of materials used", and the "Primary energy consumption" in the ecological dimension are considered critical, as well as "Working conditions", on the social dimension. Other scholars, such as Beier et al. [134], mention that in future researchers should consider economic, environmental, and societal aspects when evaluating the effects of the adoption of Industry 4.0 on sustainability.

Besides the importance of the results and conclusions drawn from this study, some limitations are identified, such as the small sample size (10 case studies); only one company from a different SC was engaged in the study which could give a biased perception.

As future research, it will be interesting to study the relationship between the implementation level of these advanced technologies and the sustainability level of digitalized SCs. That is, are the more digitalized SCs more sustainable in their behavior? It would be also interesting to analyze and test the conceptual model proposed in this study in different sectors of activities by using a cross-national survey. Another possible direction for the development of this research in the future is to understand how the Advanced Technologies most used are contributing to the SCOR processes.

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

Appendix A

Structured Interview Protocol

Part A1—Company and respondent characterization

Please indicate the following data to characterize your company and yourself:

Company Sector: ____________________	**Number of Employees:**
Primary product(s):	Country where the company operates:
Company level of expertise in Supply Chain Management 4.0 projects: Low __ Intermediate __ Advanced __	Your job title: _________________________ Your number of years in the job title: ________
Your job responsibilities: ______________________________	Your job level: Worker __ Middle Manager __ Top Manager __

How do you define your company' position in your supply chain? (Fill with an "X")
Focal company (manufacturer of a final product) ______
First-tier supplier ______
Second-tier supplier ______
Third tier supplier _______
Other. Which? _______

Part B—Supply Chain Management Advanced Technology Adoption

To which extent are the following technologies adopted by your company? Please select the options that reflect the current status of your company.

Table A1. SCOR Processes where the Advanced Technologies Are Used.

ADVANCED TECHNOLOGIES	No Adoption	PLAN	SOURCE	MAKE	DELIVER	RETURN
		Balances the Demand and Supply to Meet the Sourcing, Manufacturing and Delivering Requirements	Includes the Procurement Activities to Acquire Goods/Service	Is Related to the Transformation of Products and Services to Meet Planned and Actual Orders	Comprises the Fulfilment of Customer Demand as Requested	Is Associated to All Reverse Movements of Goods and Services from Customers for Any Reason
Data analytics/Big Data						
Visual technology (e.g augmented reality, virtual reality and holograms)						
Intelligent control systems (use of AI [Artificial Intelligence] techniques, such as expert systems, fuzzy logic, machine learning and neural networks)						
Energy saving/efficiency technology						
Smart products/parts/materials (use of tracking and tracing technology such as RFID_Radio Frequency Identification)						
Cloud computing						
Cybersecurity						
Internet of things (IoT)/internet of services (IoS)						
Cyber-physical systems (CPSs);						
Three-dimensional (3D) printing/additive manufacturing						
Advanced manufacturing (e.g., use of flexible manufacturing systems, and reconfigurable manufacturing systems)						
IT-based production management (e.g use of ERP (enterprise Resources Planning), MES (Manufacturing Execution Systems), CAD (Computer Aided Design, and CAM Computer Added Manufacturing).						

C—Sustainable Performance of a Supply Chain 4.0—KPIs Suitability Level

Considering your experience and expertise in the field, use an "X" to register your perception about the level of suitability of each Key Performance Indicators (KPI), presented in the table below, to assess the sustainable performance of a Supply Chain 4.0.

	Not Suitable	Slightly Suitable	Moderately Suitable	Very Suitable	Extremely Suitable
Economic indicators					
Total annual amount of wages and benefits given to employees by an organization.					
Total annual operating costs of an organization					
Percentage of procurement budget spent on local suppliers.					
Total annual sustainability expenditure by an organization.					
Total annual sales/revenues of the organization.					
Other(s) ________________________________ ____ ____					
Social Indicators					
Total annual number of employees in an organization.					
Total annual number of female employees in an organization.					
Total number of employees' turnover.					
Total number of employees given training in an organization.					
Total number of incidents of consumer complaints.					
Others(s) ____ ____ ______________________________________					
Environmental Indicators					
Total annual renewable energy consumption of an organization.					
Total annual volume of water recycled/reused by organization.					
Total annual amount of direct GHGs emissions by an organization.					
Total annual amount of ozone-depleting substances by an organization.					
Waste reduction.					
Total annual amount of hazardous waste generated by an organization.					
Percentage of supplier's subject to sustainability assessment.					
Percentage of local/national/provincial suppliers of an organization.					
Other(s) ________________________________ ____ ____					

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