sustainability

Article

How to Measure Sustainability in the Supply Chain Design: An Integrated Proposal from an Extensive and Systematic Literature Review

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Abstract: The increase in the world population and resource scarcity has led to the introduction of environmental concepts such as sustainability and *sustainable supply chain design* (SSCD). However, there is a lack of consensus among researchers on how to measure sustainability in SSCD. Therefore, the authors propose a novel approach to measuring sustainability in the context of SSCD by developing an integrated, tractable, and representative metrics framework. The methodology corresponds to a quantitative approach involving bibliographic examination and statistical techniques. First, the authors conducted a systematic literature review by formulating research questions and a search protocol, searched for relevant articles, and conducted a quality assessment on full-text reviews to obtain metrics for measuring sustainability in SSCD from the literature. Then, they defined aggregation criteria representing their inclusion relationship by merging associated metrics. The authors then used Cluster Analysis (CA), a multivariate statistical technique, for grouping the metrics. Consequently, twelve clusters were distinguished from 541 research articles, grouping 51 metrics from different sustainability dimensions. It shows the strong connection among the sustainability dimensions, i.e., they must be assessed holistically. Then, we proposed reducing the 51 metrics to 5 to evaluate sustainability in the SSCD, allowing us to focus on a reduced number of indicators.

Keywords: supply chain design; sustainability; cluster analysis; aggregation criteria; systematic review

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1. Introduction

The world population has doubled in the last fifty years, while vital resources have become increasingly limited [1]. However, several companies contribute more to resource depletion and environmental problems due to their increased raw material and energy consumptions [2]. In light of resource scarcity, certain environmental concepts have been incorporated into the design and management of production systems. One such concept is sustainability, which refers to the capacity of enterprises to meet their immediate financial needs while ensuring that they, as well as others, can meet their future needs without compromise [3]. From a holistic perspective, sustainability denotes a form of development that fulfills present requirements while ensuring that the capacity of future generations to fulfill their own needs remains intact [4].

The multidimensional nature of sustainability has been defined in recent literature as the strategic attainment and integration of an organization's social, environmental, economic, political, and technological aspects [5–11] through the systemic coordination of the main inter-institutional business processes [12]. Consequently, both governmental and societal concerns have been raised about environmental protection and corporate social responsibility, leading to constant pressure on companies to reassess their supply chains—not only in terms of economic objectives but also environmental, social, political, and technological concerns [13,14]. This is reflected in the increase in company sustainability reports in the last 20 years [15].

This viewpoint introduces novel factors that must be considered when designing supply chains, a practice now known as *sustainable supply chain design* (SSCD). SSCD aims to effectively measure and achieve sustainability dimensions, primarily by aligning with the Sustainable Development Goals (SDGs) outlined by the United Nations (UN) [16]. Over the past few years, numerous studies have been conducted across various production sectors, including applications within the healthcare industry [17], big data [18], fuels [19], energy [20], textile [21], and water resources [22,23].

In practice, research on SSCD has utilized a wide range of metrics and methodologies to address each dimension of sustainability [11,24,25]. Several literature reviews have demonstrated how SSCD could effectively incorporate sustainability [24,26–30]. Table 1 shows that, among the related literature reviews, those with no details regarding the years considered or number of articles reviewed correspond to narratives reviews; this means that they are based essentially on the researcher's experience [31]. In addition, Table 1 shows that by each dimension of sustainability, there are several aspects assessed. For example, regarding the environmental dimension, refs. [29,32] integrate the Eco-indicator 99 and ReCiPe 2008, each considering different impact category indicators at the midpoint (as acidification potential) or endpoint levels (as damage to ecosystem quality). On their behalf, ref. [33] assessed the use of essential resources such as land, water, and materials, as well as air pollution represented by footprints of NO_x and SO_2 emissions and fine particulate matter ($PM_{2.5}$) emissions. They also considered the damage to species richness as a consequence of pollutants, GHG emissions, and the use of land and water. Meanwhile, ref. [34] assessed the pollution emitted into air and water and considered resource consumption as energy or water. Ref. [35] considered impact categories and indicators of climate change, biochemical oxygen demand, damage to human health, and water footprint, as well as performance measures such as residual waste generated, GHG emissions, energy consumption, and amount of recycled material. With even more detail, ref. [36] described several footprints as follows. Carbon footprint or GHG footprint considers carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emissions to the atmosphere. Water footprint measures both the consumption of freshwater as a resource (including both blue and green water) and the use of freshwater to assimilate waste. The latter component refers to a greywater footprint. The ecological footprint measures land appropriation to produce renewable biomass resources and uptake waste via CO_2 sequestration. The land footprint measures the land required to supply food, materials, energy, and infrastructure, expressed in physical hectares or equivalent land units (global hectares). The nitrogen footprint measures the emissions of reactive N to the atmosphere and water bodies. The phosphorus footprint measures P's use as a resource and P's losses to water bodies. The chemical footprint accounts for all chemical substances released into the environment, which may ultimately lead to ecotoxicity and human toxicity impacts. The $PM_{2.5}$ and PM_{10} footprints measure particulate matter pollution in the atmosphere. These are also included in the chemical footprint. The ozone footprint measures the emission of gases controlled or due to be controlled under the Montreal Protocol in terms of ozone-depleting potential weighted kilograms. The material footprint measures the use of materials from a consumption perspective, allocating all globally extracted and used raw materials to domestic final demand (metal ores, nonmetallic minerals, fossil fuels, and biomass (crops, wood, wild fish catch, etc.)). Finally, biodiversity loss measures the impact as a result of different pressures, such as land and water use or chemical pollution.

Table 1. Related literature review assessment.

Ref	Years	N articles	Sustainability Dimensions		
			Economic	**Social**	**Environmental**
[37]	1997–2010	36	Total cost, net revenue	Profit sharing, employment, and income distribution	LCA-based environmental impacts: energy demand and CO_2 emissions, natural capital, or resources
[28]	January 2008 to October 2020	354		Customer service level, attendance to demand, and reduction of work accidents	CO_2 emission, use of energy and/or the number of tailings
[30]		54	Total annualized supply chain cost, annualized profit, total profit, revenue, NPV	Accrued jobs, land use changes, traffic annoyance	GHG emissions, Eco-Indicator 99, non-renewable energy use, water use, pollution, CO_2 emissions, Impact 2002+
[29]	1995–2017	188	Overall costs, NPV, raw material availability and energy potential, payback period calculation, prices, energy potential	Incomes, calorie consumption, energy access, people in water stressed areas, child deaths, employment, health and safety	Eco-indicator 99; ReCiPe, GHG emissions, cumulated energy demand, global warming potential, acidification potential, primary energy use, land use efficiency, energy consumption, particle emissions, agriculture land use, climate change.
[38]	1997 to July 2016	146	Total cost, risks on investment, efficiency, NPV, total profits, financial revenue, total transportation cost, logistics cost of raw material collection, transport distance, unit cost, economic potential, conditional value-at-risk, marginal delivery cost	Job opportunity, social impact, number of workers, total service level	GHG emissions, total GHG emission savings, net energy out, environmental impact, global warming potential
[39]	Up to Dec. 2019	112	Resource productivity indicator, total costs	Job creation	Waste and emissions related, CO_2 emissions, GHG emissions, Eco-Indicator 99, non-renewable energy use, water use and pollution, Impact 2002+
[40]	2000–2015	over 20,000	Cost of production	Food security, human health	GHG emissions, air quality (non-GHGs emissions), soil resources, land use change, water resources

Table 1. *Cont.*

Ref	Years	N articles	Sustainability Dimensions		
			Economic	**Social**	**Environmental**
[41]	2000 to 2014/2015		Net income from sales, productivity in primary feedstock production, number, and capacity of routes for critical distribution systems, capacity use and flexibility, gross value added, energy diversity	Employment created, incidences of occupational injury, illness and fatalities in the production process, uncertainty of tenure and land rights	GHG emissions in production, soil organic carbon maintained, non GHG emissions, water withdrawn, pollutant loadings to waterways and bodies of water related to raw material obtention, area and percentage of lands of high biodiversity converted for production, net energy ratio in individual process steps, the change in diversity of total primary energy supply
[32]				Employment, occupational accidents, unemployment, hazardous work, vulnerable employment, social security, access to clean water	GHG emissions and the use of basic resources, air pollution, damage to species richness, energy consumption, waste production, CO_2 emissions
[33]	2008–2019	132			Pollution, soil degradation, product losses and waste, GHG emission, resources consumption, environmental damage or stress
[35]					Carbon footprint, water footprint, ecological footprint, land footprint, nitrogen footprint, phosphorus footprint, chemical footprint, PM2.5 and PM10 footprints, ozone footprint, material footprint, biodiversity loss
[42]		78	Economic performance, financial performance	Human rights, community development	Low-carbon products, low-carbon logistics, low-carbon production, energy consumption
[24]	2000-2015	190	Production performance metrics	Product safety, work safety	Ecological footprint, emissions, pollution
[36]	2012–2015	979	Total supply chain cost, net revenue, profit		GHG emissions
[43]	2006–2016	85	Profitability, cost, revenues, NPV	Job generation, food security, respects for property land rights, social acceptability, working conditions	GHG emission, waste management, wastewater management, biodiversity conservation and protection, energy efficiency

Table 1. *Cont.*

Ref	Years	N articles	Sustainability Dimensions		
			Economic	**Social**	**Environmental**
[44]	1997–2012	71	Overall cost, overall profit, NPV, financial revenue, risk on investment, transport cost	Number of jobs, social footprint	GHG emissions, maximize energy return in the conversion facility, minimize energy used in the supply chain, maximize net energy profit
[27]		10 Reviews + 188 articles	Cost reduction, profit, NPV, expected return, economic output, financial risk, total value of purchasing	Service level, number of accrued jobs, hours of employment, injury rate, satisfaction levels of stakeholders and customers, social risks	GHG emissions, energy consumption and water consumption, waste production, CO_2 equivalent, CO_2 emission per capita, embodied carbon footprint, air pollution, global warming
[45]	1999 to May 2016	220	Cost, profit, NPV, risk	Job creation, safety, health, number of working hours, discrimination, satisfaction, and poverty aspects	Global warming, LCA impacts, waste reduction, recycling, biodiversity, renewable energy consumption
[46]	1995–2018	198		Number of jobs created by the supply chain, number of workdays missed by employees due to health problems, ethical supply chains, equitable treatment of stakeholders, education and training, social justice, and diversity.	CO_2 emissions, natural resources utilization, and product recovery
[29]	2000–2017	50	Profit, cash flow, delivery lead time, customer satisfaction, trade level, budget variance, total cost, capacity utilization, production effectiveness, product quality	Employment, occupational health and safety, local communities, food to energy competition, jobs created, job opportunities created, social benefits	Eco-Indicador 99, Recipe 2008, Impact 2002+, global warming potential, pollution, CO_2 emissions, NO_2 emission, CO emission, volatile organic compounds, water usage, green appraisal scores, carbon trading, new technologies, new material for products, water quality, fossil fuel consumption
[47]	1900–2018	40	Total cost, total profit, inventory, routing costs, product waste cost	Storage and distribution of infectious medical waste and hazardous material, customer dissatisfaction	Total carbon emissions from logistics operations, carbon emissions by pricing them, reducing waste generation, collection of waste

Table 1. *Cont.*

Ref	Years	N articles	Sustainability Dimensions		
			Economic	**Social**	**Environmental**
[48]			Net cash flow generated	Employment	Net GHG emissions, emissions from carbon stock change due to land use, potential environmental risk, land use intensity, energy use, materials use, fertilizer and pesticide use, chemicals used for raw material obtention, water use, wastewater to be treated
[49]	2015–2018	113	Reliability, responsiveness, flexibility, financial performance, quality, transportation costs and establishment costs of facilities, logistics activity costs, purchasing, carbon emission cost, profit, total cost, NPV	Work condition, human health and safety, societal commitment, customer issues, business practices	Environmental management (environmental certification owned by the company), use of resources (use of raw or recycled material, water, and energy from the surrounding area), pollution (methane (CH4) and nitrous oxides (NOx), carbon dioxide CO_2)), dangerousness, natural environment
[34]	1990–2014	87	Cost of facility investment, feedstock purchase and transportation, pollution cost, logistics costs, total annual cost, wastewater treatment costs	Work conditions, social commitment, customer issues, human rights, and business practice	Methods (Eco-Indicator 99, Impact 2002+, CML92, Recipe), Impact category and indicators
[50]	2005–2016	333	Total cost, service quality	Customer service level	CO_2 emission
[51]			Food versus fuel debate, efficiency, and energy balance, and increasing biofuel budget programs	Poverty reduction potential, land and crop indirect impacts, and effects on social resources, such as water utility systems	GHG emission, water resources quality, soil degradation and loss of biodiversity
[26]	1987 to March 2019	247	Total cost, profit, NVP	Food quality and safety, food security, social welfare, job generation and equality, supporting small enterprises, public and dietary health, consumer price fairness, food donation, corporate social responsiveness investment, social cost of GHG emissions	Carbon footprint and emissions, biomass energy production, waste disposal and food loss, land use and erosion, energy consumption, water use and contamination, LCA impacts, freshness-keeping effort, green effort, organic agriculture

Note that frequently up to one metric is assessed by sustainability, which varies depending on the research [37,50]. It implies several possible metric combinations for the SSCD, considering the large number of metrics that can be evaluated for each sustainability dimension [37,50]. Thus, it should be emphasized that there is currently a lack of consensus among researchers regarding the optimal metrics to accurately represent each sustainability dimension and how to depict the overarching concept of sustainability within the framework of supply chain design. This research tendency has implied different approaches and metrics to assess sustainability and, then, the following question emerges: *How do you measure sustainability in sustainable supply chain design (SSCD)?*

It leads to the need for a comprehensive and integrated framework to depict the sustainability measure in the SSCD, evidence of at least two new significant problems to be addressed [52–55]. First, adopting multiple metrics to evaluate each sustainability dimension could search for a feasible solution, ideally optimal, by any resolution method approach. Second, a particular solution from a limited set of metrics could have substantive differences in terms of results in comparison with another metric's selection, seeking an isolated goal and avoiding a comprehensive vision of sustainability and the relationships of its components [50]. In addition, similar metrics could be considered in more than one dimension. For instance, both logistic cost (from the economic dimension) and greenhouse gas (GHGs) emissions by transport (from the environmental dimension) require distance between the supply chain actors as a parameter for their computation. Another example is total carbon emission (from the environmental dimension) and the carbon emission cost (from the economic dimension), where the former, weighted by the carbon cost parameter, provides the latter.

Our Contribution

In this paper, the objective is to propose an integrated, tractable, and representative metrics framework to measure the five sustainability dimensions: Economic, Social, Environmental, Political, and Technological, which allows us to address the problems related to measuring sustainability in the sustainable supply chain design (SSCD). This research is based on a quantitative approach involving mainly bibliographic examinations and multivariate relational and statistical techniques. To our best knowledge, this report describes a novel approach that has not been followed in previous research in a sustainable setting. Formally, our contributions are threefold: First, we conduct an exhaustive literature review to analyze the measuring of each of the five sustainability dimensions. This process follows a systematic literature review process through a practical and methodological analysis, distinguishing temporal trends, countries, the main production sectors, methodologies, decision-making levels, and metrics considered to measure each sustainability dimension from 541 published papers available in the Web of Science (WoS) database, until the year 2020. Second, we work on the above-obtained results and develop an integrated metrics framework based on *aggregation criteria* and Cluster Analysis (CA) methods. It allows for the representation and identification of the relations among different parameters and metrics to be computed/optimized in each of the five sustainability dimensions in SSCD from the literature. In addition, it provides a systemic scheme to incorporate other new metrics from future research. In practice, we propose 12 clusters and a reduced group of metrics to measure sustainability as a basis for novel decision-aid models for production systems and logistics design. It will support and facilitate sustainability management in supply chain design for decision makers in the industry. Third, we discuss our findings and their theoretical and managerial implications, leaving open questions to be addressed in future work about sustainability in SSCD and providing insights from our results to guide answers from research and practice perspectives.

The paper is structured as follows, Section 2 introduces the proposed methodology by integrating a literature review and statistical analysis. Section 3 presents relevant results regarding trends in supply chain scientific literature and sustainability measure identification. Then, Section 4 describes the implications of those results on measuring sustainability in supply chain design. Finally, Section 5 presents an overview of the main results and their implications as well as future research questions.

2. Materials and Methods

2.1. Literature Review

To conduct our exhaustive and systematic literature review, we adopted the search methodology for a systematic literature review presented by [56] because it generalizes the stages and steps for a successful literature review. This methodology includes three major stages: (i) planning the review, (ii) conducting the review, and (iii) reporting the review. The initial phase involves recognizing the need for a review, determining research queries, and constructing a review protocol. The subsequent stage entails identifying and selecting primary studies and extracting, analyzing, and synthesizing pertinent data. Lastly, the third stage involves the dissemination of the resultant findings.

In particular, the research questions for the initial phase are defined as follows:

- What methodologies have been used to measure sustainability in the SSCD?
- At what decision-making level has sustainability been measured in the SSCD?
- How has sustainability been measured in the SSCD?

Then, the review protocol considers as keywords the concepts related to these questions, which are formulated as the search string: ((“Green Supply Chain” OR “Sustainable Supply Chain”) AND (Design OR Conception)) OR ((“Supply Chain Design”) AND (Sustainable OR Sustainability)). Note that the search string does not include *decision making* or *metric*-related keywords in order to not restrict the search.

In the second stage, we establish a search strategy corresponding to search articles available in the Web of Science (WoS) database, which is widely regarded as the foremost scientific citation search and analytical information platform [57]. This search strategy focuses on articles published up to December 2020, utilizing keywords that are searched for within the database’s Title, Abstract, and Keywords sections. Note that no initial date was selected to identify the first related literature. The inclusion criteria involve evaluating whether the research articles identified are relevant to the research queries. Furthermore, the screening procedure involves the initial review of the titles and abstracts to identify articles that satisfy the inclusion criteria, as Figure 1 shows. Then, in the third stage, we performed a refined quality assessment on a full-text review to select the articles for data extraction. After the literature search and selection, the literature assessment focused on the research questions defined for the data analysis, particularly to obtain the metric used for measuring the sustainability in SSCD from the literature.

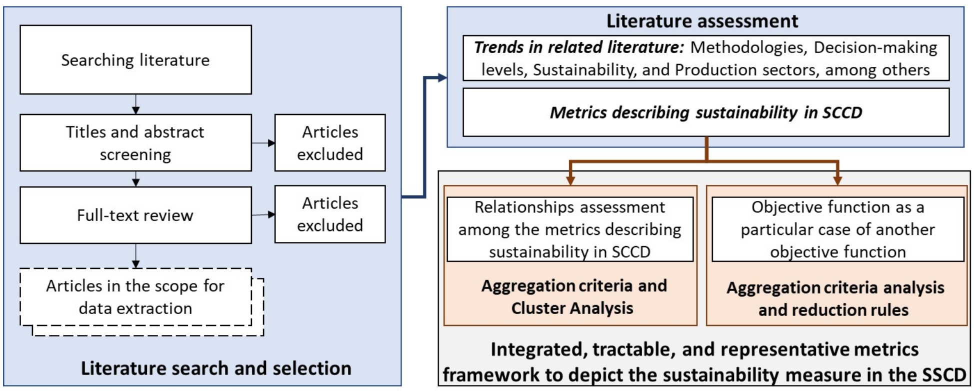

Figure 1. Methodology followed to develop an Integrated, tractable, and representative metrics framework to depict the sustainability measure in the SSCD.

2.2. Aggregation Criteria, Cluster Analysis (CA), and Reduction Rules

Specifically, we determined parameters and metrics from the literature assessment and defined *aggregation criteria* to represent the inclusion relationship between them. It is formally defined as follows: “An element (A) aggregates another element (B) if and only if the element (B) correspond to the previous calculations required to obtain the value of the element (A)". For example, profit maximization (A) integrates the total supply chain costs (B_1) and the revenues (B_2) by adding them. This reduction follows similar initiatives in other research communities, such as the scheduling setting, where the reduction allows the representation and identification of the relations among different parameters and objective functions of the scheduling problems (see the "scheduling zoo" initiative in [58] for details). To our best knowledge, this report describes a novel approach that has not been followed in previous research in a sustainable setting. In this case, we formally identify and define sets of parameters, auxiliary metrics, and final metrics from the measuring analysis of sustainability in SSCD provided by the literature review, stating the relationships between them based on the defined aggregation criteria. We remark that the final metrics are stated from the metrics recognized from the literature review, merging other associated metrics. The parameters and auxiliary metrics are identified from the considered final metrics.

This procedure allows for assessing the relationship among the different metrics, as Figure 1 presents, to analyze the interrelationship among the sustainability dimensions. To analyze it, we consider the multivariate statistical technique, Cluster Analysis (CA), which groups elements to achieve the maximum homogeneity within each group and the highest difference between groups based on the relationships among the metrics [59]. CA can be performed in Gephi open-source software for graph and network analysis [60]. The obtained results allow the construction of a set of directed acyclic graphs, where a directed arrow represents the aggregation criteria to a single metric from the aggregated metric. In this representation, we remark that many metrics can aggregate a metric, and the node size of each metric is directly defined by its number of aggregated metrics. In practice, we obtain an interconnected network among all parameters and metrics used to measure sustainability in the SSCD. In this network, the sustainability dimensions integrated into each cluster and the relationships among the clusters would lead to understanding the interrelationship among the sustainability pillars.

Furthermore, to introduce the reduction rules, consider pollution generation and the pollution cost. In this case, one metric is contained in the other because a pollution cost factor is multiplied by the pollution production. Then, the pollution cost can be understood as a more complex metric or integrated at a higher level. Therefore, the objective is to identify the metrics at the higher level of integration. It would lead us to understand which metrics are a particular case of another metric. Finally, the more complex metrics or objective functions could be selected to measure sustainability in SSCD from five dimensions: Economic, Social, Environmental, Political, and Technological, since they all integrate other metrics.

3. Results

3.1. Literature Assessment

Following the review protocol, we found and scrutinized 1147 articles, of which only 541 research articles met the refined quality standards required for data extraction. During the initial screening, 422 articles were excluded, of which 63 were review articles, 82 did not involve supply chain design, 152 evaluated sustainability drivers, and 125 performed sustainability effects evaluations. The latter two categories involved ex post assessments, which were not within the scope of this research focusing on ex ante assessments. Additionally, 184 articles were excluded from the full-text review, of which four were review articles, 32 did not perform supply chain design, 85 evaluated sustainability drivers, and 63 assessed sustainability effects.

This section details the data extracted from the 541 research articles to solve the research questions presented in the previous section.

3.1.1. Trends in Related Literature

What methodologies have been used to measure sustainability in the SSCD?

The analysis of research articles based on methodology reveals that the majority, 62.85%, employ optimization models (O), followed by evaluation studies (Ev) with 17.01%, and simulation (S) with 10.91%. These details are depicted in Figure 2. The combined use of optimization and simulation (O-S) amounts to 3.14%, while only three articles employ optimization, simulation, and evaluation (O-S-Ev) jointly [61–63].

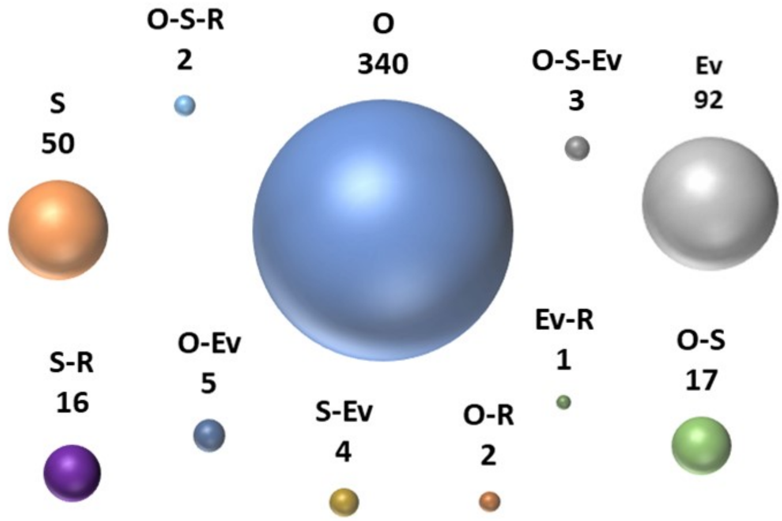

Figure 2. Assessing the methodologies applied for SSCD. Optimization (O), evaluation (Ev), simulation (S), literature review (R).

Most of the research articles classified as optimization developed mixed-integer linear programming models [64–67]. However, mixed-integer nonlinear programming models were also presented [68–70]. Research articles integrating several decision-making levels mainly develop two-stage models to incorporate uncertainty [70–74]. Even though stochastic mixed-integer linear fractional programming models to tackle multiple uncertainties regarding feedstock supply and product demand were developed [75]. Furthermore, research articles that assessed several sustainability dimensions frequently integrated multiple objective functions [65,73,74,76–78]. These multi-objective models have been solved with the Epsilon-constraint method [79,80]; particle swarm [67]; weighted sum methods, such as weighted Tchebycheff and augmented weighted Tchebycheff [66,77]; genetic algorithms [67,70], such as non-dominated sorting genetic algorithm [81], non-dominated sorting genetic algorithm-II [82], and tabu search [83], among others. In addition, game-theoretic approaches seeking optimal supply chain configurations were found [84,85]. Furthermore, DEMATEL methodology [86] and intuitionistic fuzzy-TOPSIS [87] have been applied to evaluate the suppliers' characteristics for its selection. Besides, other evaluation research articles address the environmental impacts of the supply chain through the Life Cycle Assessment [88]. The methodologies applied in the simulation research articles include Multi-agent-based simulation [89], Discrete Event Simulation [90], and System Dynamics [91]. Furthermore, the research articles, including optimization and simulation, applied Monte Carlo to address uncertainty effects on supply and demand [92,93]. Even when optimization is the most used methodology to integrate sustainability in the supply chain design, future research should include uncertainty studies through evaluations or simulations.

At what decision-making level has sustainability been measured in the SSCD?

In the literature, three levels of supply chain decision making are distinguished according to the time horizon, the uncertainty, and the activities involved [94]. The strategic level at the base of the decision-making structure covers decisions such as facility location, storage capacity, production capacity, and supplier selection, among others [95]. These are long-term decisions taken with high levels of uncertainty, and they are the basis of tactical and operational decisions, designing the principal supply chain structure [96]. The tactical level covers aspects such as production and distribution planning, production allocation, transport capacities, inventories, and the management of safety stocks [97]. Finally, at the top is the operational level, integrating short-term or daily decisions, such as job execution, vehicle loading, unloading, and order delivery [98]. These decisions involve lower uncertainty degrees than the other decision-making levels. Consequently, we classify the research articles selected by the following criteria. A document accounting for the strategic decision-making level must address a long planning cycle of several years. Furthermore, a research article considering the tactical decision-making level deals with a shorter planning cycle (6 months to a year). Meanwhile, the research articles on the operational decision-making level involve weekly or daily planning tasks.

Figure 3 shows the number of publications assessing the different decision-making levels, either individually or integrated.Although it exhibits that the authors have focused mainly on the strategic aspects, in percentage terms, 41.96% of the research articles studied consider only decisions at the strategic level mainly related to supplier selection [99–102] and facility location [78,103], 5.18% involve decisions from the tactical level related to inventory strategies [104–106] and 18.11% only assess decisions from the operational level, devoted to scheduling [107], pricing [108–111], and transportation decisions [109,112,113], among others. The above reflects the essential importance of the strategic decision-making level in the supply chain. Furthermore, only 27 research articles consider the three decision-making levels, such as in [114–124], mainly developing models with more than one stage. This reduced the number of research articles due to the requirements for complex models and significant computational calculations, compared with the integration of one decision-making level, in the search for an optimal supply chain, considering optimization is the main approach used in the SSCD, as Figure 2 shows.

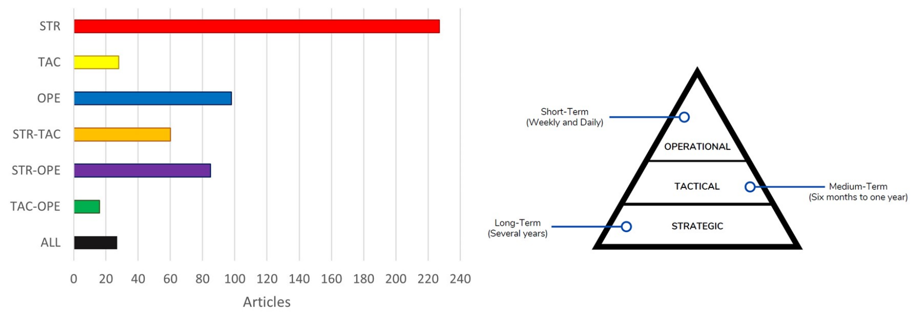

Figure 3. Decision-making levels. Strategic (STR); tactical (TAC); operational (OPE).

Related to the supply chain decision-making levels considered in the SSCD, we observed that at least 34% of the research articles integrate more than one level. Moreover, they provide interesting proofs in an integrated SC design, considering different planning horizons, indicating the need for uncertainty inclusion in the SSCD.

How has sustainability been measured in the SSCD?

Figure 4 shows the distribution of research articles according to the dimension of sustainability covered. Furthermore, 28% of the research articles integrate economic and environmental aspects; 17% focus on economic, social, and environmental dimensions (a set of dimensions called *triple bottom line* (TBL)); 11% corresponds to research articles devoted only to environmental aspects; the economic dimension is studied in isolation by 9%; and 5% of the research articles focus only on social aspects. It shows that environmental and economic aspects lead the sustainability studied in SSCD.

Only seven research articles integrate the extended definition of sustainability (i.e., environmental, economic, social, political, and technological), published between 2010 and 2020. Dev and Shankar [115] extend the knowledge of the limits of green supply chain management (GSCM) elaborated by [125] by finding a hierarchy of interactions between the sustainable boundary enablers with interpretive structural modeling methodology. The boundaries include environmental, economic, cultural, legal, political, technological, and temporal aspects.

Then, in the context of energy transition policy, ref. [126] investigate whether reframing the bioenergy supply chain design can allow sustainable regional development targets.The enablers studied include environmental factors, such as reduced agricultural fertilizer use, economic aspects such as biogas filling station installation, social aspects such as satisfying biogas demand, political aspects such as converting public sector vehicles to biogas, and technological aspects, such as stabilizing manure processing. Finally, ref. [127] focused on supporting managerial decision making based on a Delphi with domain experts and literature synthesis in the same trend. The supply chain activities ranked include the reduction of pollution to air, water, and land, minimizing energy and material consumption, reducing noise levels, utilizing renewable and alternative forms of inputs, and the discussion, investigation, and selection of alternative methods/options.

Ref. [128] developed a model for SSCD based on the ANP (analytic network process) methodology. It presents a case study applied to the electrical goods industry in Germany assessing environmental criteria (ISO 14001), windows for delivery, occupational health and safety (ISO 45001), corporate social responsibility (CSR), demand volume customers influence on distribution and manufacturing orders, and the duration of the product lifecycle.

Furthermore, ref. [82] focuses on Phase III biorefineries (mix feedstock and multiple products) in the Colombian context and develops a multiobjective optimization model solved with an adapted non-dominated sorting genetic algorithm II (NSGA II). It assesses the property concentration of cultivable lands, the net present value and transportation costs, the potential workstations, the governmental subsidies for the industry, and compare production technologies.

Meanwhile, ref. [129] investigates the impact of information sharing on the decisions and profits of the manufacturer and the retailer. The developed game theory models aim for the equilibrium of both the manufacturer and the retailer profits, including aspects such as the environmental impact of a product, promotional campaigns to capture the consumers' attention, expected consumer surplus, subsidy policies to encourage consumers to purchase, and new technology to manufacture green product introduction by the manufacturer. Finally, ref. [130] developed research for hydrogen fuel cell vehicles applied to the Occitania Region in France, seeking an optimal hydrogen supply chain with the sequential application of an optimization strategy and a multi-criteria decision-making tool. The optimization model presents a social cost-benefit analysis, including CO_2 and pollution emissions, platinum depletion, externality costs and net present value, noise, a subsidy policy scenario assessment, and the evaluation of different production technologies.

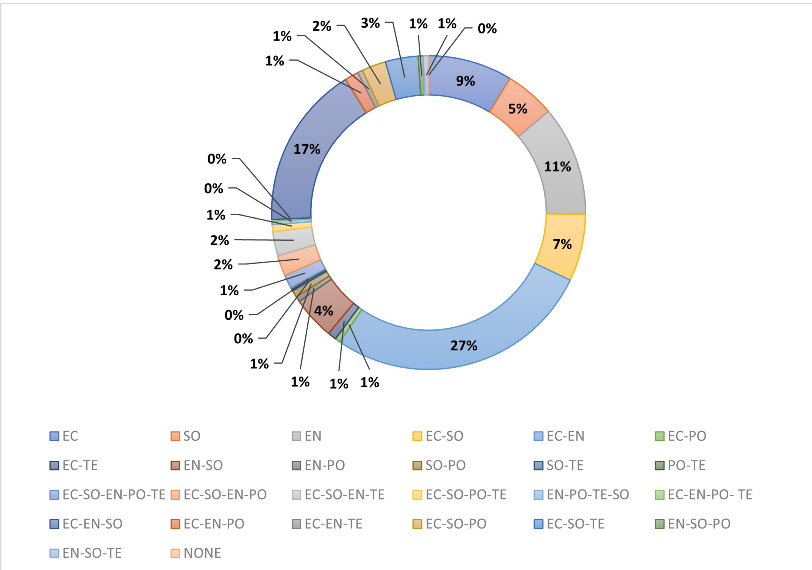

Figure 4. Sustainability dimensions. Economic (EC), social (SO), environmental (EN), political (PO), technological (TE).

The Supplementary Materials shows the research articles' classification in detail according to the methodological analysis performed in this work.

3.1.2. Metrics Describing Sustainability in SCCD

Considering most of the research articles related to the SSCD are approached by optimization, the metrics describing sustainability could be represented as objective functions. Thus, Figure 5 presents a detailed description of the 51 objective functions to be optimized from the 541 research articles studied. Note that a number is given for each objective function (metric) in the second column, this number facilitates the relationship between the definition and the acronym presented in the Appendix B.

The main objective functions and optimization criteria considered to assess the economic aspect are minimizing total costs, maximizing profits, and minimizing transportation costs. Likewise, the main objectives sought in the social dimension are the maximization of job opportunities and social welfare. Regarding the environmental dimension, the main aim is to minimize CO_2 emissions, environmental impact, GHG emissions, and water use. Finally, for the political and technological aspects, it is sought to increase the high-quality green products in the market, assure food security, maximize the desired effects of the regulations, and minimize the related cost of innovative production technologies.

It is worth noting that economic functions constitute the majority (16 objective functions), followed by environmental functions (15 objective functions). Additionally, seven objective functions can be categorized into more than one dimension of sustainability, denoted by an asterisk in Figure 5. For instance, reducing taxes paid corresponds to the economic dimension, while it is also related to tax collection in the political dimension. Besides, maximizing high-quality green goods and/or services could be classified into social or political sections. Finally, the cost and net present value related to technologies could be classified in the economic section.

It should be noted that the objective functions described in this study apply to a general SSCD. Hence, some objective functions may be more suitable for a particular SSCD than others. Furthermore, the analysis identified 51 objective functions, leading to a many-objective optimization problem. Solving such a problem results in a set of nondominated solutions known as a Pareto-optimal set (POS) or Pareto front [131]. However, solvers for such problems are sensitive to the number of objectives considered, as computational costs increase with more objectives, making solution visualization and analysis more complex [45,132]. Therefore, considering the large number of sustainability metrics and the need for an integrated approach to SSCD, it is crucial to develop efficient many-objective models and dimensionality reduction techniques that effectively address different aspects of sustainable development [51].

Other topics such as the distribution of research articles focused on SSCD by year, the number of related research article applications in the SSCD by country, and the main production sectors in SSCD development are analyzed from the literature review. These allow us to evidence the SSCD as a relevant topic worldwide with the constant growth of related research articles. Furthermore, the leading countries are Iran and China, who focus on goods production, such as automotive and manufacturing products. However, Latin America, the Caribbean, and Africa were left behind. In the same vein, much remains to be done related to using residues in producing new products, fuels, and energy. See details in Appendix A.

Dimensions	Objective function (n°)	Description
Economic (EC)	Min number of facilities (1)	It seeks to minimize the number of production plants, warehouse locations, among other facilities type
	Max production (2)	Pursues to maximize the production of goods and/or services, considering productive factors
	Max capacity use (3)	Seeks to maximize the use of productive capacity of the implemented plants
	Max revenue (4)	Maximize the enterprise incomes
	Min taxes* (5)	Minimize the taxes paid by companies
	Min the distance (6)	Minimize the distance among the organizations in the SC
	Min transportation costs (7)	Minimize the freight transportation cost related to distances among the organizations in the SC
	Min logistics costs (8)	Seeks to minimize the freight transportation cost and warehousing cost
	Min maintenance costs (9)	Seeks to minimize maintenance costs, both of machinery and infrastructure, depending on technology and production capacity
	Min production costs (10)	Seeks to minimize unit production costs, depending on raw material acquisition cost, besides the technology and production capacity for raw material transformation
	Min waste costs (11)	Seeks to minimize costs associated with waste treatment, for example disposal costs
	Min emissions costs (12)	Minimize costs associated with the release of pollutant emissions
	Min environmental costs (13)	Seeks to minimize the costs related to pollutant emissions and waste treatment
	Min total costs (14)	It seeks to minimize the total costs related to the production, environment release, transportation, and sale of the good and/or service. It is worth mentioning that it does not include investments
	Max profit (15)	Maximize the gross profit margin. Revenues, costs, and taxes are considered
	Max Net Present Value (NPV) (16)	Maximize the discounted NPV at a given interest rate. This includes investments and profits (revenues, costs, and taxes)
	Max profitability (17)	Seeks to obtain the highest possible financial returns. This includes investments and profits (revenues, costs, and taxes)
Social (SO)	Max job opportunities (18)	Seeks to maximize the fixed and variable employment opportunities generated
	Max local job opportunities (19)	Seeks to maximize the fixed and variable employment opportunities generated in determined geographical locations
	Min workplace injuries (20)	Seeks to reduce occupational accidents related to the technology implemented in the facilities
	Min days lost due to workplace accident (21)	Seeks to have the least number of days with leaves for accidents caused in the work environment related to the production technologies implemented in the facilities
	Max social impact (22)	It covers four dimensions, related by weights that reflect their relative importance. The first corresponds to maximize fixed and variable employment opportunities and reduce work damages related to production technologies. Subsequently, it assesses the facilities' implementation impact through indicators like GDP, Gini index, level of unemployment, and income by zone. Finally, it seeks to reduce the number of hazardous materials released into the environment and the food safety impacts related to raw material type consumption
	Max consumer surplus (23)	Seeks to maximize consumer benefits in social and economic terms. It is the difference between the highest price that a consumer tends to pay for certain goods and the actual market price of those goods
	Min delivery time (24)	Seeks to reduce consumer waiting times associated with delivery, depending on the average delivery time to each client
	Max Customer Service Level (CSL) (25)	CSL is defined as the proportion of customer demand that will be met
	Max customer satisfaction (26)	It considers several aspects related by weights that reflect their relative importance. It includes receiving the service in less time, geographic coverage, maximize the distance between communities and undesirable facilities implementation, meeting the demand (CSL), and maximize the high-quality goods or services delivered to the customer
	Max social welfare (27)	Social welfare mainly includes consumer surplus (CS), producer surplus (PS), environmental benefits (EB), and economic benefits (EI) of green products. PS refers to the difference between the lowest supply price of the production factors and the actual market price. EB refers to the total benefit of green products in reducing global warming, among other environmental impacts. EI refers to the budget surplus following government implementation of the financial policy as subsidies and the economic benefits for the industry. Furthermore, some researchers include in social welfare measure aspects as job creation, customer satisfaction or social impact. Therefore, social welfare relates these aspects by weights that reflect their relative importance or risk aversion coefficients
	Min dismissals (28)	Seeks to reduce the components or machine number while enhancing system reliability. Redundancy is denoted as the use of functionally similar components together, so that if a component fails, the redundant part would be available to carry out the required task without failure toward enhancing system reliability
Environmental (EN)	Min $CO2$ emissions (29)	Seeks to reduce the emission of CO_2 released into the atmosphere
	Min GHG emissions (30)	Seeks to minimize the greenhouse gases emissions such as CO, CO_2, N_2O, CH_4 and O_3
	Min fuel consumption (31)	Seeks to minimize fuel consumption throughout the SC
	Min energy consumption (32)	Seeks to minimize the energy consumed by the entire SC
	Max performance raw materials (33)	Seeks to increase the sustainable materials acquisition
	Min water consumption (34)	Seeks to reduce water use in the SC
	Min wastewater production (35)	Seeks to reduce wastewater production in the SC
	Max sustainable suppliers in SC (36)	Seeks to increase the choice of sustainable suppliers to the SC
	Min waste (37)	Seeks to minimize waste generated throughout the SC
	Min hazardous materials (38)	Seeks to reduce the use of hazardous materials required for production
	Max recycled water (39)	Seeks to maximize water recovered from the SC
	Max waste recovery (40)	Seeks to increase waste recovery, whether in the same SC or another
	Min pollutant emissions (41)	Seeks to minimize pollutant emissions as greenhouse gas emissions (CO_2eq), formation of fine particles ($PM_{2.5}$eq), or phosphorus (P eq) release in freshwater producing eutrophication. These pollutant emissions are related to fuel combustion, wastewater and waste production, pollution related to infrastructure implementation, and raw material related pollution, considering the SC entirely
	Min transport impact (42)	Seeks to reduce the impact of transportation in terms of environmental pollution related to fuel combustion
	Min Environmental Impact (43)	Seeks to minimize the environmental impact generated by the release of pollutant emissions, shortage of fossil resources and water consumption. Mainly measured by Life cycle assessment applying methods as the Recipe, Eco-Indicator 99, CML, Carbon footprint, Water footprint, among others
Technological (TE)	Max Technology implementation (44)	It pursues a greater incorporation of technological tools or production technologies, such as software, hardware, methodologies, among others
	Min Costs in Technologies* (45)	Seeks to reduce costs associated with innovative production technologies
	Max Products with incipient technology (46)	Seeks to increase the production of goods and/or services with emerging technology
	Max the net present value (NPV) of technology investments* (47)	Seeks to maximize net present value by considering the investment in technologies
Political (PO)	Max Tax Revenue or Collection* (48)	Seeks to understand the associated effects when the government seeks to maximize tax revenues or collection
	Min Government Expenditure (49)	Seeks to minimize state expenditures, mainly related to public policy as subsidies and tax reduction, and understand the effects when trying to reduce the government spending
	Max green quality products production* (50)	Pursues to maximize the production of high quality green good and/or services, considering productive factors
	Max food security* (51)	Seeks for food security for the community reducing the food related raw materials use due to governmental requirements

Figure 5. Detailed objective functions found in the research articles reviewed. The objective functions that can be categorized into more than one dimension of sustainability are denoted by an asterisk.

3.2. The Aggregation Criteria and Cluster Analysis (CA)

From the above literature review, 51 objective functions (metrics) are recognized to be considered in the measure of sustainability in the SSCD by the decision maker.

To start the aggregation criteria, we initially merge the objective functions n° 16 and n° 47 associated with the net present value (NPV) (see Figure 5). Thus, we formally consider 50 final objective functions (metrics) and identify 58 auxiliary functions and sets of 48 parameters, stating the relationships among them based on the defined aggregation criteria.

The obtained results are described in detail in Appendix B and allow us to construct a set of directed acyclic graphs. The aggregation criteria are represented by a directed arrow to a single objective function from the aggregated function, as shown in Figure 6. Note that many objective functions can aggregate an objective function, and the node size of each one is directly defined by its number of aggregated functions. For instance, the total greenhouse gas emissions in the supply chain (TGHGESC) involve waste, wastewater, transport, production, and infrastructure GHG emissions. The total production cost (TPC) involves the raw material acquisition, water, energy, and fuel costs. Furthermore, social welfare (TSW) integrates the NPV, ROI, consumer surplus, social impacts, capacity use, environmental impacts, health impacts, and weighted customer satisfaction.

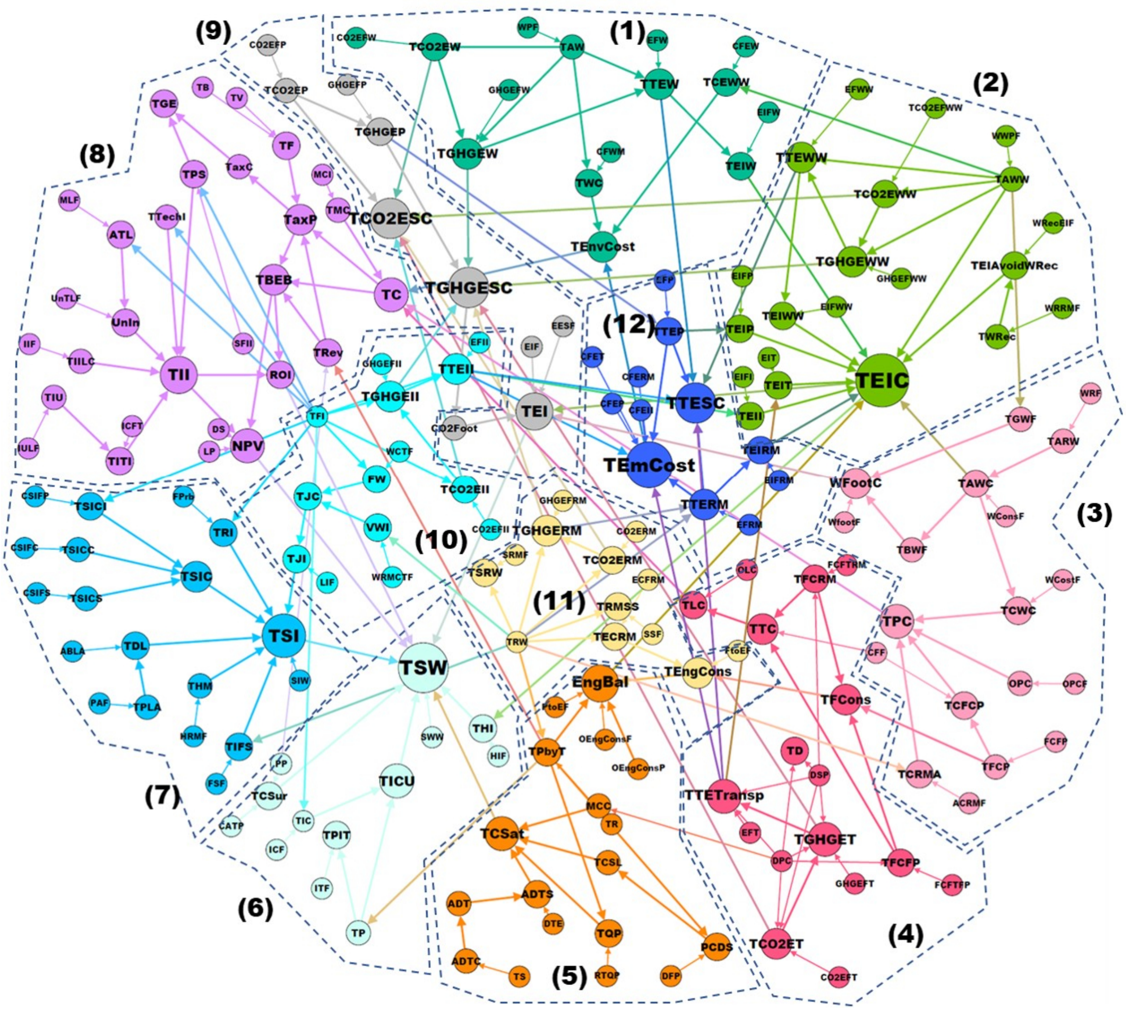

Figure 6. Objective functions relationship diagram.

By considering the relationships among the final objective function, auxiliary function, and parameters based on the defined aggregation criteria, we analyze and reduce the number of functions to measure sustainability by considering the multivariate statistical technique called the cluster analysis (CA) method [59]. It provides a graph and network analysis using Gephi open-source software [60]. Figure 6 shows the results obtained, where the relationship between the parameters, auxiliary functions, and final functions allows us to identify 12 clusters, which are colored to improve the visualization of each one. In addition, we analyzed the cluster in terms of sustainability dimensions involved by its parameters and functions, as Table 2 shows.

Table 2. Cluster analysis according to the addressed sustainability dimensions. Economic (EC), social (SO), environmental (EN), political (PO), technological (TE).

Area	Dimension	Description
(1)	EC - EN	This cluster is related to waste generation by considering the waste emission amounts and their environmental and economic impacts.
(2)	EN	This cluster is related to wastewater generation by considering the wastewater emission amounts and their environmental and economic impacts. In addition to the total avoided emissions related to waste recovery.
(3)	EC–EN	This cluster is the economic and environmental impacts related to fuel, raw materials, and water consumption in production.
(4)	EC–EN	It involves the environmental impacts related to fuel consumption in transport, as well as the logistics cost.
(5)	EN–SO	This cluster includes consumer satisfaction and energy balance linked through the production assessment. It involves customer satisfaction by considering the maximum customers coverage, the customer service, quality of products, and delivery time to customers.
(6)	EC–EN–SO	It involves social welfare linked to other clusters, in addition to the total capacity use, the consumer surplus, and the health impacts related to the supply chain emissions.
(7)	EN–SO–PO	This cluster involves the social impact by considering hazardous materials used, occupational accidents, infrastructure redundancy, social impact according to geographic characteristics by considering the customers and suppliers' geographical selection, and food security.
(8)	EC–TE–PO	It includes the governmental expenditures related to subsidies and taxes, the investment related to infrastructure implementation as well as the financial metrics: net present value and return on investment.
(9)	EN	This cluster involves the total greenhouse gas emissions in the supply chain and the environmental impact related to all the emissions in the supply chain.
(10)	EN–SO	This cluster assesses the infrastructure implementation by considering the emission amounts generated and their environmental impacts, in addition to the number of infrastructures implemented and the job creation impact related to Gini Index, poverty levels, gross domestic product, among others.
(11)	EN	It includes the emissions related to the raw material acquisition as well as its sustainable classification. Besides, the energy consumption links this cluster with clusters 4 and 5 to reach the energy balance calculation..
(12)	EC–EN	It involves the total emissions cost and the total emissions produced in all the supply chain stages.

Concerning the cluster assessment, we note that each cluster involves a different stage in the supply chain. For instance, cluster 8 includes the infrastructure and technologies implementation for production operations, while Cluster 10 evaluates the impact of this implementation. Then, cluster 11 considers the provisioning stage, while cluster 4 evaluates the transport in the entire supply chain. Cluster 3 includes the consumables necessary for production, such as water, fuel, and raw materials, while Cluster 9 measures the emissions generated in production. Clusters 1 and 2 measure emissions of waste and wastewater generated in the production stage. Clusters 5 and 6 refer to the distribution of products by measuring customer satisfaction and surplus. Finally, cluster 12 measures the costs of all emissions generated in the supply chain, while cluster 8 assesses the financial aspects of the supply chain. Then, this distinction of metrics by cluster allows us to distinguish what material flow and information (parameters) are required to assess sustainability in each section or stage of the supply chain.

Regarding the sustainability dimensions involved in each cluster, we remark that the environmental and economic dimensions are in eleven (92%) and six (50%) clusters, respectively. It shows the importance of environmental and economic dimensions in the SSCD and their relation with the other dimensions to be evaluated. The social and political dimensions are in four (33%) and two (17%) clusters, respectively. In contrast, the technological dimension is in only one cluster (8%), evidencing the incipient assessment and relations of these aspects in SSCD. Furthermore, considering the interactions among the sustainability dimensions, five (42%) clusters simultaneously assess the economic and environmental metrics. Meanwhile, four (33%) clusters integrate environmental and social metrics, while three (25%) only assess environmental metrics. It defends the hypothesis of the possibility of finding similarities between the metrics, grouping them despite belonging to different dimensions of sustainability. In addition, it shows the strong interrelationship among all the sustainability pillars, which reinforces the need for a holistic assessment of sustainability.

Additionally, at larger nodes, which represent a larger number of function and parameter aggregations, we can highlight metrics such as TEIC. It aggregates the environmental impacts by categories, including those associated with wastewater, waste, transportation, and production. Similarly, TEmCost considers the costs associated with the emissions generated throughout the entire supply chain, also accounted for as emissions in the TTESC metric. TSI represents the social impact and includes the impact on food safety, infrastructure redundancy, accidents associated with production technologies, the impact of implementing facilities according to the selected geographical location, and the impact associated with the fixed and variable work generated. Finally, TSW represents social welfare and incorporates several sustainability dimensions by evaluating the importance of net present value, return on investment, environmental impact, impact on human health, and social impact, among others. By including various metrics of several sustainability dimensions, this is observed as an alternative to the inclusion of sustainability to all its extensions through weighting the metrics it incorporates.

3.3. The Aggregation Criteria and Reduction Rules

Then, to understand which metrics are a particular case of another, we have developed Figure A2 in Appendix C. It separates the metrics by level, increasing in level as metrics are added. Then, we have a set of five metrics representative of sustainability as follows: (1) total social welfare (TSW), (2) total products obtained with incipient technologies (TPIT), (3) total raw materials acquired from sustainable suppliers (TRMSS), (4) total sustainable raw material used (TSRM), and (5) total governmental expenditures (TGE). Note that TSW integrates: net present value (NPV), return over investment (ROI), total social impact (TSI), total environmental impact (TEI), total human impact (THI), total consumer satisfaction (TCSat), total consumer surplus (TCSur), and total implemented capacity use (TICU). This reduced number of metrics to consider when integrating sustainability in the SSCD is a manageable number for both multi-objective optimization and decision-maker assessments. Furthermore, these five metrics at the higher level of integration consider the five sustainability dimensions: Economic, Social, Environmental, Political, and Technological. Finally, note that TSW could be the only metric assessing sustainability by considering weights to integrate TPIT, TRMSS, TSRM, and TGE.

4. Discussion

The proposed integrated metrics framework provides decision makers in the industry with a systematic approach to defining and integrating sustainability metrics in sustainable supply chain design (SSCD). This framework will allow decision makers to identify and prioritize sustainability metrics and facilitate decision making in SSCD.

The metrics assessment based on aggregation criteria and cluster analysis (CA) method offers an integrated view of the relationship between the metrics and the sustainability pillars. It reveals the holistic nature of sustainability and indicates that the sustainability dimensions should not be analyzed separately but as a whole. This task is complex to perform if we consider the different sustainability measurement guides or even the UN sustainable development goals, which consider a large number of indicators to be evaluated. In the SSCD context, the large number of metrics found in the related literature show this complexity. Therefore, the reduced group of metrics proposed to measure sustainability will simplify the process of measuring sustainability in SSCD and reduce the burden of considering an unmanageable number of metrics. It will support and facilitate sustainability management in supply chain design for decision-makers in the industry.

In addition, this proposal made tractable the SSCD problem from an optimization point of view since it enables researchers and practitioners to design optimal sustainable supply chains through the typical multi-objective solution methods to evaluate five objective functions.

The proposed framework lays the basis for novel decision-aid models for production systems and logistics design. Because this research was focused on the strategic decision-making level, further research could assess the ex post assessments following the proposed methodology to identify and integrate the sustainability metrics.

5. Conclusions

This paper proposes an integrated, tractable, and representative metrics framework to measure the five sustainability dimensions in the sustainable supply chain design. This research has been based on an exhaustive and systematic literature review, multivariate relational statistical techniques, and reduction rules. To our best knowledge, this report describes a novel approach that has not been followed in previous research in a sustainable setting.

In the review process, 541 research articles were analyzed in depth, where most of the literature assesses strategical decisions by applying optimization as the principal methodological approach. Other topics observed from the literature review allowed us to expect a clear linear research trend for evaluating sustainability aspects in the SSCD, identifying that the principal research countries seeking SSCD are Iran, China, and the United States of America, which are focused mainly on the automotive sector and consumer goods production. Furthermore, the sustainability dimensions most studied are economical and environmental. Fifty-one metrics to measure sustainability in the SSCD are described based on the literature review. Among these, 16 correspond to the economic aspects, 15 to environmental, 12 to social, and 4 to political and technological dimensions. They can be understood as objective functions to be optimized, considering optimization is the most applied methodology. From the sustainability metrics recognized in the literature, we identify parameters and auxiliary functions by applying the aggregation criteria. Then, the cluster analysis obtained 12 clusters showing the strong interrelationship among the sustainability dimensions. Finally, following the reduction rules, a reduced number of 5 objective functions to measure sustainability in the SSCD is proposed, evidencing the measure of social welfare as a potential metric to integrate all sustainability dimensions.

Consistently, interesting practical and policy implications emerge from the research. Firstly, it reveals the exponential growth of SSCD-related research since formulating the Sustainable Development Goals in 2015. As a result, it has led to an unmanageable number of metrics to consider when integrating sustainability into supply chain design. Secondly, the research proposes a limited set of metrics that make optimization tractable through different methodologies to solve the SSCD multi-objective problem. Thirdly, the proposed limited set of metrics facilitates decision making for stakeholders by reducing the number of indicators to observe to make a decision. This research has important implications for supporting the integration of sustainability in productive sectors by providing a managerial-level understanding and allowing the development of optimized supply chain structures for sustainability.

The proposed methodology provides a systemic framework to incorporate additional metrics or objective functions. Hence, considering this research work conducted a literature review up to December 2020, it is advisable to conduct periodic updates every five years.

For future research, some associated research questions are proposed to be addressed, which could facilitate the sustainability measure and analysis in the design problem of a sustainable supply chain:

1. How do we integrate the different objective functions in an index/value of sustainability in SSCD?
2. How do we define a validation process for it?

The first question invites us to study and analyze these research results from multi-objective and many-objective optimization perspectives to obtain an index/value of sustainability in SSCD, considering the unique features of each productive sector. It requires analyzing and evaluating the five metrics found with a higher level of integration since they could be integrated into a unique metric by weighting them according to their relevance. Moreover, the relevance of each metric could vary depending on the production sector (energy, waste, water, and others) and the organizational setting. This leads to the second question, which is about defining a validation process based on historical management reports and expert knowledge from relevant actors such as government authorities, industry, and the community.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su15097138/s1, Table S1: Research articles classification according to the methodological analysis, Table S2: Details for the objective functions found in the research articles reviewed [2,21,61–79,79–93,99–113,115,116,118,120–124,126–130,133–201,201–608].

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Appendix A. Other Topics Analyzed from the Literature Review

Appendix A.1. Temporal Trends

Figure A1 presents the distribution of research articles focused on SSCD by year of publication. A clear linear trend evidences the growing interest in integrating sustainability aspects into supply chain design. The highest number of publications was in 2018, with 111 research articles representing 20.52%. Besides, 2011 and 2015 present the highest increased percentages compared to the previous year, reaching an increase of 200%. Furthermore, the annual growth trends observed in Figure A1 should continue in the coming years due to the social, academic, governmental, and industrial compromise with sustainable development [25,609]. Indeed, future trends of literature, considering a linear regression over the data with a coefficient of determination (r^2) 94.91%, would reach around 192 research articles for 2030, i.e., an annual growth of approximately nine research articles per year. Finally, it is worth mentioning that this literature review considers the articles published until 31 December 2020.

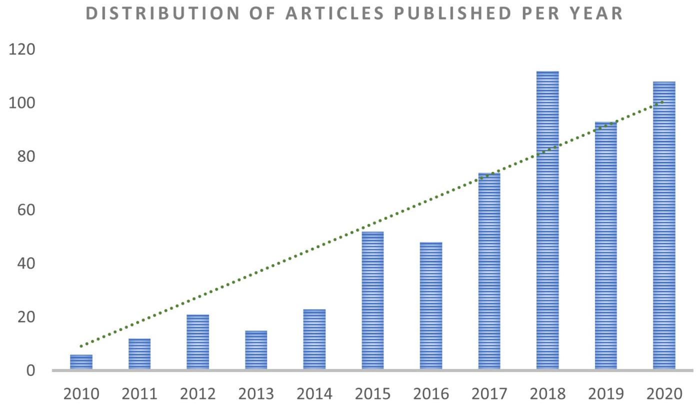

Figure A1. Distribution of articles published per year.

Appendix A.2. Countries Exploring the SSCD

Considering the number of related research articles applications in their territory, we highlight Iran and China, with 38 publications each. For Iran, the main areas explored are the automotive sector industries, including tire production [137,266,471] and transportation [201,499]. For China, the most critical study area is consumer goods production, as in [68,86,89,91,143,160,203,300,324,437,441], followed by the recycling area, as in [150,159,407,476]. Then, the US has 24 applied research articles, mainly related to biorefineries as in [72,75,139,141,151,161,202,472,500,502–504], followed by the research articles devoted to the consumer goods production as in [147,248,299,352]. In the case of India, most of the 19 research articles devoted are related to the production of goods, as in [99,133,134,144,146], focused on the automotive and textile sectors. The following countries, the UK (8), France (7), Germany (6), and Australia (4), represent 4.62% of the research articles. We should underline that most of the research articles present mathematical models tested with theoretical data.

Appendix A.3. Main Production Sectors in SSCD Development

The key sectors involved in developing SSCD are categorized into different areas, including goods production, industries, ecological products, biorefinery, bioenergy and energy production, waste, biomass, and others. The breakdown of these categories can be found in Table A1. Notably, Goods Production refers to final products intended for immediate consumption, while Industries focus on intermediate goods like raw materials used to produce final goods.

Table A1. Number of publications per area.

Production Sectors	Numbers of Publications	Percentage
Goods production	142	26.25%
Industries	62	11.46%
Ecological products	52	9.61%
Biorefinery	31	5.73%
Bioenergy	29	5.36%
Waste	14	2.59%
Biomass	6	1.11%
Others	205	37.89%
TOTAL	541	100%

The majority of the research articles focus on producing goods, accounting for 26.06% of the total. The final goods predominantly studied include electrical components [152,406,477], mobile phones [474], food and perishable items [226,473,507], textiles [21,148], automotive products [107], and manufacturing items [156]. Another significant category is industries, which represent 11.65% of the research articles, with a particular emphasis on the [157], Cement [200,475], Foundry [155], and Mining sectors [375]. The remaining 9.61% of research articles cover ecological products, and this category mainly comprises studies on closed-loop supply chains, with the goal of increasing the reuse and recycling of elements [66,78,227]. They also study meaningful aspects, such as the price competitiveness between ecological and conventional products [77,84,138].

Furthermore, 5.36% of the research articles correspond to biorefinery studies [82,153,472]. It mainly refers to using second-generation raw materials, i.e., organic waste, to produce energy products, such as biofuels, chemical components, food, and fertilizers. Meanwhile, out of the 29 research articles classified within the bioenergy category, the majority are focused on the production of biofuels using first-generation raw materials [440], i.e., using biomass that is more than often edible, or second-generation raw materials [136,267,438,506], often waste materials such as agricultural or municipal residues. By applying this process within industries, the aim is to maximize energy efficiency and production. Furthermore, certain research papers aim to establish a sustainable supply chain within the refinery sector [500,501]. As an illustration, ref. [154] formulated an efficient and sustainable supply chain for natural gas components intending to maximize overall profits while minimizing total greenhouse gas emissions and water consumption. Additionally, alternative energy sources like hydrogen are evaluated [130,158,348,505].

Research articles focused on waste aim to diminish the environmental impact by preventing waste generation, ultimately decreasing greenhouse gas emissions [149,199,389,406,439,479]. Thus, these articles examine the effect of waste supply chain management decisions on the environment in search of greater efficiency [112]. Various waste management scenarios, including Recycling, Landfill, Incineration, and Reuse, are analyzed to assess their effects. That research concludes that supply chain management is critical in reducing environmental impact [149].

For the study of biomass, six publications focused on the reduction of carbon dioxide and costs to create a sustainable industry [135,140,142,145,247,489]. They mention the management of sewage, fertilizers, and agricultural residues to strategically position biomass plants to harvest and collect the product easily. While all articles point to biomass supply chains, different factors and geographical regions are studied. For example, ref. [140] assess the effect of biomass availability uncertainty in Mexico based on historical data. Instead, ref. [247] seek the optimal location, technology, and capacity of the operating facilities in combination with the optimal technology to harvest and collect products for biomass supply chains in Europe.

Appendix B. Parameter and Function Descriptions with Acronyms and Aggregation Criteria

Appendix B.1. Parameter Description and Acronyms

Table A2. Parameters description and acronyms.

Acronym	Parameters Description
ABLA	Average number of business days lost due to accidents in production plants
ACRMF	Acquisition cost factor according to the raw material type and supplier
CATP	The highest price that a consumer tends to pay for certain goods
CFEII	Cost factor per emissions by type, released in infrastructure implementation
CFEP	Cost factor per emissions by type, released in production
CFERM	Cost factor per emissions by type, released in raw material procurement
CFET	Cost factor per emissions by type, released in transportation
CFEW	Cost factor per emission by type, released in wastewater
CFF	Cost factor per fuel

Table A2. *Cont.*

Acronym	Parameters Description
CFWM	Cost factor per type of waste management
CO2EFII	CO_2 emission factor related to infrastructure implementation by technology and capacity
CO2EFP	CO_2 emission factor according to fuel consumption in production
CO2EFT	CO_2 emission factor according to fuel consumption in transport
CO2EFW	CO_2 emission factor according to waste type
CO2ERM	CO_2 emission factor related to raw material procurement
CSIFC	Category of social impact factor by customer location
CSIFP	Category of social impact factor (Gini / Poverty / GDP / Income) by production plant location
CSIFS	Category of social impact factor by supplier location
DFP	Demand factor per product by each customer
DPC	Distance between each plant and customer
DS	Discount rate
DSP	Distance between each supplier and plant
DTE	Delivery time expected
ECFRM	Energy consumption factor for raw material production by raw material type and supplier
EESF	Effect on ecosystem factor, from ReCiPe (a method for the impact assessment in a Life Cycle Assessment), related to environmental impact by impact category
EFII	Emission generation factor by type other than GHG, in infrastructure implementation
EFP	Emission generation factor by type other than GHG, related to production
EFRM	Emission generation factor by type other than GHG, related to raw material type
EFT	Emission generation factor by type other than GHG, in transport
EFW	Emission generation factor by type other than GHG, in waste
EFWW	Emission generation factor by type other than GHG, in wastewater
EIF	Environmental impact factor weighting categories as carbon footprint, water footprint, and other environmental impact categories.
EIFI	Environmental impact factor by impact category, according to location, technology, and capacity implemented
EIFP	Environmental impact factor by impact category, related to production
EIFRM	Environmental impact factor by impact category, related to raw material production by raw material type and supplier
EIFW	Environmental Impact factor by impact category, related to emissions type b from waste
EIFWW	Environmental impact factor by impact category, related to emissions type from wastewater
EIT	Environmental impact factor by impact category, related to emissions type from transport
FCFP	Fuel consumption factor for production according to raw material type, technology, and capacity implemented
FCFTFP	Fuel consumption factor by final products transport, according to weight and distance
FCFTRM	Fuel consumption factor by raw material transport, according to weight and distance
FPrb	Faillure probability
FSF	Food safety impact as binary factor, according to raw material type consumed and supplier
FtoEF	Fuel to energy factor, depending on fuel type, as gasoline, electricity, among others
GHGEFII	GHG emission factor related to infrastructure implementation, other than CO_2
GHGEFP	GHG emission factor according to fuel consumption in production, other than CO_2
GHGEFRM	GHG emission factor related to raw material procurement, other than CO_2
GHGEFT	GHG emission factor according to fuel consumption in transport, other than CO_2

Table A2. *Cont.*

Acronym	Parameters Description
GHGEFW	GHG emission factor according to waste type, other than CO_2
GHGEFWW	GHG emission factor in wastewater, other than CO_2
HIF	Health impact factor related to the environmental impact categories
HRMF	Hazardous raw materials factor, according to raw material type
ICF	Installation capacity factor
ICFT	Investment costs factor by production technology implementation
IIF	Infrastructure investment factor, according to location and capacity
ITF	Incipient or emerging technology binary factor
IULF	Investment uncertainty level factor for each production technology, according to its maturity level
LIF	Category of social impact factor related to the total job created, considering geographical characteristics as GDP, GINI, unemployment, or income, among others
LP	Length of the evaluation period
MCI	Maintenance cost factor according to the raw materials processed depending on technology, capacity, and location implementation
MLF	Maturity level factor by production technology
OEngConsF	Other energy consumption in supply chain factor.
OLC	Other logistic costs
OPCF	Production cost factor according to raw material type, technology, and capacity implemented, without fuel, water, and energy-related costs
PAF	Number of potential accidents according to technology factor
PP	Product price
PtoEF	Product to energy factor
RTQP	Rate of transformation in quality products, according to technology and raw material used
SFII	Subsidy factor for investments in infrastructure depending on government incentives
SIW	Social impact weight
SRMF	Sustainable raw materials factor, according to raw material type
SSF	Sustainable supplier factor, according to supplier location
SWW	Social welfare weight
TB	Tax base
TCO2EFWW	CO_2 emission factor in wastewater
TR	Transformation rate according to raw material type, technology, and capacity implemented
TS	Transport average speed km/h
TV	Variation of taxes depending on Government Incentives
UnTLF	Uncertainty related to the technology readiness level factor
WfootF	Water foot factor
WConsF	Water consumption factor according to raw material type processing, technology, and capacity implemented
WCostF	Water cost factor
WCTF	Number of workers required according to capacity and technology
WPF	Waste production factor by type a, according to raw material type, technology, and capacity implemented
WRecEIF	Waste recovery environmental impact factor
WRF	Water recycling factor possible depending on the production technology and raw material used
WRMCTF	Number of workers required to process a type of raw material according to production technology and plant capacity
WRRMF	Waste recovery raw materials factor, according to raw material type
WWPF	Wastewater generation factor, according to raw material type processed, technology, and capacity implemented

Appendix B.2. Main Objective Function Description and Acronyms

Table A3. Main objective function description and acronyms.

n°	Acronym	Function Description
(1)	TFI	Total number of facilities installed
(2)	TP	Total number of products by type, produced in a certain location with a certain technology
(3)	TICU	Total installed capacity use
(4)	TRev	Total revenues
(5)	TaxP	Tax Paid
(6)	TD	Total distance in the supply chain network
(7)	TTC	Total transportation costs
(8)	TLC	Total logistics costs
(9)	TMC	Total maintenance costs
(10)	TPC	Total production costs
(11)	TWC	Total waste costs
(12)	TEmCost	Total emission costs
(13)	TEnvCost	Total environmental costs
(14)	TC	Total costs
(15)	TBEB	Total business economic benefits
(16–47)	NPV	Net present value including technology investments
(17)	ROI	Return over the investment (Profitability)
(18)	TJC	Total job opportunity created
(19)	TJI	Total job opportunity created impact
(20)	TPLA	Total number of potential labor accidents, according to plant location, capacity and production technology
(21)	TDL	Total days lost due to accidents in production plants
(22)	TSI	Total social impact
(23)	TCSur	Total customer surplus
(24)	ADT	Average delivery time
(25)	TCSL	Total customer service level
(26)	TCSat	Total customer satisfaction
(27)	TSW	Total social welfare
(28)	TRI	Total redundancy infrastructure
(29)	TCO2ESC	Total CO_2 emissions in the supply chain
(30)	TGHGESC	Total GHG emissions in the supply chain
(31)	TFCons	Total fuel consumption
(32)	TEngCons	Total energy consumption
(33)	TSRW	Total quantity of sustainable raw materials purchased
(34)	TAWC	Total amount of water consumed
(35)	TAWW	Total amount of wastewater produced in raw material transformation

Table A3. *Cont.*

n°	Acronym	Function Description
(36)	TRMSS	Total quantity of raw materials purchased to sustainable suppliers
(37)	TAW	Total amount of waste generated by production
(38)	THM	Total hazardous materials
(39)	TARW	Total amount of recycled water
(40)	TWRec	Total waste recovery
(41)	TTESC	Total emissions by type in the supply chain
(42)	TTETransp	Total emissions by type in the transport
(43)	TEIC	Total environmental impact by impact category
(44)	TTechI	Total technologies implemented
(45)	TITI	Total investment required for production technology implementation
(46)	TPIT	Total number of products produced with incipient technology
(48)	TaxC	Tax collection
(49)	TGE	Total government expenditure
(50)	TQP	Total quantity of quality products
(51)	TIFS	Total impact on food safety

Appendix B.3. Auxiliary Function Description and Acronyms

Table A4. Auxiliary function description and acronyms.

n°	Acronym	Auxiliary Function Description
(52)	TRW	Total quantity of raw material acquired by type and supplier
(53)	TCO2ERM	Total CO_2 emissions from raw material
(54)	TGHGERM	Total GHG emissions from raw material
(55)	TPbyT	Total product by type of final product
(56)	TEIRM	Total environmental impact by category, depending on the production of each type of raw material
(57)	TGHGEII	Total GHG emissions from infrastructure implementation
(58)	TCO2EII	Total CO_2 emissions from infrastructure implementation
(59)	TTEII	Total emissions by type from infrastructure implementation
(60)	TEII	Total environmental impact by category, depending on infrastructure implementation
(61)	TEI	Total environmental impact in ecosystem
(62)	TGHGEW	Total GHG emissions from waste
(63)	TTEW	Total emissions by type from waste
(64)	TCO2EW	Total CO_2 emissions from waste
(65)	TEIW	Total environmental impact by category, related to waste
(66)	TGHGEWW	Total GHG emissions in wastewater
(67)	TTEWW	Total emissions by type in wastewater

Table A4. *Cont.*

n°	Acronym	Auxiliary Function Description
(68)	TCO2EWW	Total CO_2 emissions in wastewater
(69)	TEIWW	Total environmental impact by category, related to wastewater
(70)	TCEWW	Total cost related to emissions in wastewater
(71)	THI	Total environmental impact on health
(72)	OEngConsP	Other energy consumption in production
(73)	TFCFP	Total fuel consumption by final product transport
(74)	TFCRM	Total fuel consumption by raw material transport
(75)	EngBal	Energy Balance in the supply chain
(76)	TFCP	Total fuel consumption for production
(77)	CO2Foot	Carbon footprint
(78)	TGHGEP	Total GHG emissions from fuel in production
(79)	TGHGET	Total GHG emissions from transport
(80)	TCO2EP	Total CO_2 emissions from fuel consumption in production
(81)	TCO2ET	Total CO_2 emissions from transport
(82)	TEIP	Total environmental impact by category, depending on production
(83)	TCRMA	Total cost of raw material acquisition
(84)	TGWF	Total gray water footprint
(85)	OPC	Other production costs related to raw material type, technology, and capacity implemented, without fuel, water, and energy
(86)	TCWC	Total cost of water consumption
(87)	TBWF	Total blue water footprint
(88)	TEIT	Total environmental impact by category, depending on transport
(89)	TTEP	Total emissions by type related to production
(90)	TECRM	Total energy consumed due to the production of raw materials
(91)	TCFCP	Total cost related to fuel consumption in production
(92)	TF	Tax fraction
(93)	TPS	Total plant installation subsidy
(94)	TIU	Total investment uncertainty
(95)	TIILC	Total installation investment according to location and capacity
(96)	TII	Total infrastructure and technology investment
(97)	ATL	Average technology level
(98)	TSICI	Total average social impact by impact category such as GDP, GINI, unemployment, or incomes according to infrastructure location implementation
(99)	TSICC	Total average social impact by impact category such as GDP, GINI, unemployment, or income according to customer location selection
(100)	TSICS	Total average social impact by impact category such as GDP, GINI, unemployment, or income according to supplier selection
(101)	TSIC	Total average social impact by impact category such as GDP, GINI, unemployment, or income according to geographic selection for plants, supplier, and customer
(102)	FW	Fixed number of workers required by plant

Table A4. *Cont.*

n°	Acronym	Auxiliary Function Description
(103)	VWI	Variable number of workers required by infrastructure
(104)	ADTC	Average delivery time to each client
(105)	ADTS	Average delivery time satisfaction
(106)	PCDS	Percentage of each customer demand satisfied, per product type
(107)	TTERM	Total emissions by type related to raw material procurement
(108)	MCC	Maximum coverage of customers reached, considering all customers and plants
(109)	TIC	Total installed capacity
(110)	TEIAvoidWRec	Total environmental impact avoided by category related to waste recovery
(111)	UnIn	Uncertainty in infrastructure investment related to the technology readiness level
(112)	WFootC	Water foot impact by categories

Appendix B.4. Relationship Description among the Parameters, Main Functions (Metrics), and Auxiliary Functions

Table A5. Relationship among the parameters, functions, and auxiliary functions (relationship weight equal to 1.5 for relationships with parameters and a weight equal to 2 for relationships among functions).

Source		End		Relationship Weight
n°	*Acronym*	n°	*Acronym*	
	ABLA	(21)	TDL	1.5
	ACRMF	(83)	TCRMA	1.5
(24)	ADT	(105)	ADTS	2
(104)	ADTC	(24)	ADT	2
(105)	ADTS	(26)	TCSat	2
(97)	ATL	(111)	UnIn	2
	CATP	(23)	TCSur	1.5
	CFEII	(12)	TEmCost	1.5
	CFEP	(12)	TEmCost	1.5
	CFERM	(12)	TEmCost	1.5
	CFET	(12)	TEmCost	1.5
	CFEW	(70)	TCEWW	1.5
	CFF	(91)	TCFCP	1.5
	CFF	(7)	TTC	1.5
	CFWM	(11)	TWC	1.5
	CO2EFII	(58)	TCO2EII	1.5
	CO2EFP	(80)	TCO2EP	1.5
	CO2EFT	(81)	TCO2ET	1.5
	CO2EFW	(64)	TCO2EW	1.5
	CO2ERM	(53)	TCO2ERM	1.5

Table A5. *Cont.*

Source		End		Relationship Weight
n°	***Acronym***	**n°**	***Acronym***	
(75)	EngBal	(43)	TEIC	2
	FCFP	(76)	TFCP	1.5
	FCFTFP	(73)	TFCFP	1.5
	FCFTRM	(74)	TFCRM	1.5
	FPrb	(28)	TRI	1.5
	FSF	(51)	TIFS	1.5
	FtoEF	(32)	TEngCons	1.5
(108)	MCC	(26)	TCSat	2
	MCI	(9)	TMC	1.5
	MLF	(97)	ATL	1.5
(16-47)	NPV	(27)	TSW	2
	OEngConsF	(75)	EngBal	1.5
(72)	OEngConsP	(75)	EngBal	2
	OLC	(8)	TLC	1.5
(85)	OPC	(10)	TPC	2
	OPCF	(85)	OPC	1.5
	PAF	(20)	TPLA	1.5
(77)	CO2Foot	(61)	TEI	2
	CSIFC	(99)	TSICC	1.5
	CSIFP	(98)	TSICI	1.5
	CSIFS	(100)	TSICS	1.5
	DFP	(106)	PCDS	1.5
	DPC	(108)	MCC	1.5
	DPC	(81)	TCO2ET	1.5
	DPC	(6)	TD	1.5
	DPC	(73)	TFCFP	1.5
	DPC	(79)	TGHGET	1.5
	DPC	(42)	TTETransp	1.5
	DS	(16–47)	NPV	1.5
	DSP	(81)	TCO2ET	1.5
	DSP	(6)	TD	1.5
	DSP	(74)	TFCRM	1.5
	DSP	(79)	TGHGET	1.5
	DSP	(42)	TTETransp	1.5
	DTE	(105)	ADTS	1.5
	ECFRM	(90)	TECRM	1.5
	EESF	(61)	TEI	1.5
	EFII	(59)	TTEII	1.5

Table A5. *Cont.*

Source		End		Relationship Weight
n°	*Acronym*	n°	*Acronym*	
	EFP	(89)	TTEP	1.5
	EFRM	(107)	TTERM	1.5
	EFT	(42)	TTETransp	1.5
	EFW	(63)	TTEW	1.5
	EFWW	(67)	TTEWW	1.5
	EIF	(61)	TEI	1.5
	EIFI	(60)	TEII	1.5
	EIFP	(82)	TEIP	1.5
	EIFRM	(56)	TEIRM	1.5
	EIFW	(65)	TEIW	1.5
	EIFWW	(69)	TEIWW	1.5
	EIT	(88)	TEIT	1.5
(102)	FW	(18)	TJC	2
	GHGEFII	(57)	TGHGEII	1.5
	GHGEFP	(78)	TGHGEP	1.5
	GHGEFRM	(54)	TGHGERM	1.5
	GHGEFT	(79)	TGHGET	1.5
	GHGEFW	(62)	TGHGEW	1.5
	GHGEFWW	(66)	TGHGEWW	1.5
	HIF	(71)	THI	1.5
	HRMF	(38)	THM	1.5
	ICF	(109)	TIC	1.5
	ICFT	(45)	TITI	1.5
	IIF	(95)	TIILC	1.5
	ITF	(46)	TPIT	1.5
	IULF	(94)	TIU	1.5
	LIF	(19)	TJI	1.5
	LP	(16-47)	NPV	1.5
(17)	ROI	(27)	TSW	2
	RTQP	(50)	TQP	1.5
	SFII	(93)	TPS	1.5
	SIW	(22)	TSI	1.5
	SRMF	(33)	TSRW	1.5
	SSF	(36)	TRMSS	1.5
	SWW	(27)	TSW	1.5
(106)	PCDS	(25)	TCSL	2
	PP	(23)	TCSur	1.5
	PP	(4)	TRev	1.5
	PtoEF	(75)	EngBal	1.5

Table A5. *Cont.*

Source		End		Relationship Weight
n°	*Acronym*	n°	*Acronym*	
(39)	TARW	(34)	TAWC	2
(37)	TAW	(64)	TCO2EW	2
(37)	TAW	(62)	TGHGEW	2
(37)	TAW	(63)	TTEW	2
(37)	TAW	(11)	TWC	2
(34)	TAWC	(87)	TBWF	2
(34)	TAWC	(86)	TCWC	2
(34)	TAWC	(43)	TEIC	2
(35)	TAWW	(70)	TCEWW	2
(35)	TAWW	(68)	TCO2EWW	2
(35)	TAWW	(43)	TEIC	2
(35)	TAWW	(66)	TGHGEWW	2
(35)	TAWW	(84)	TGWF	2
(35)	TAWW	(67)	TTEWW	2
(48)	TaxC	(49)	TGE	2
(5)	TaxP	(48)	TaxC	2
(5)	TaxP	(15)	TBEB	2
	TB	(92)	TF	1.5
(15)	TBEB	(16-47)	NPV	2
(15)	TBEB	(17)	ROI	2
(87)	TBWF	(112)	WFootC	2
(14)	TC	(5)	TaxP	2
(14)	TC	(15)	TBEB	2
(70)	TCEWW	(13)	TEnvCost	2
(91)	TCFCP	(10)	TPC	2
	TCO2EFWW	(68)	TCO2EWW	1.5
(58)	TCO2EII	(29)	TCO2ESC	2
(58)	TCO2EII	(57)	TGHGEII	2
(80)	TCO2EP	(29)	TCO2ESC	2
(80)	TCO2EP	(78)	TGHGEP	2
(53)	TCO2ERM	(29)	TCO2ESC	2
(53)	TCO2ERM	(54)	TGHGERM	2
(29)	TCO2ESC	(30)	TGHGESC	2
(81)	TCO2ET	(29)	TCO2ESC	2
(81)	TCO2ET	(79)	TGHGET	2
(64)	TCO2EW	(29)	TCO2ESC	2
(64)	TCO2EW	(62)	TGHGEW	2

Table A5. *Cont.*

Source		End		Relationship Weight
n°	*Acronym*	n°	*Acronym*	
(68)	TCO2EWW	(29)	TCO2ESC	2
(68)	TCO2EWW	(66)	TGHGEWW	2
(83)	TCRMA	(10)	TPC	2
(26)	TCSat	(27)	TSW	2
(25)	TCSL	(26)	TCSat	2
(23)	TCSur	(27)	TSW	2
(86)	TCWC	(10)	TPC	2
(21)	TDL	(22)	TSI	2
(90)	TECRM	(32)	TEngCons	2
(61)	TEI	(27)	TSW	2
(110)	TEIAvoidWRec	(43)	TEIC	2
(43)	TEIC	(61)	TEI	2
(43)	TEIC	(71)	THI	2
(60)	TEII	(43)	TEIC	2
(82)	TEIP	(43)	TEIC	2
(56)	TEIRM	(43)	TEIC	2
(88)	TEIT	(43)	TEIC	2
(65)	TEIW	(43)	TEIC	2
(69)	TEIWW	(43)	TEIC	2
(12)	TEmCost	(13)	TEnvCost	2
(32)	TEngCons	(75)	EngBal	2
(13)	TEnvCost	(14)	TC	2
(92)	TF	(5)	TaxP	2
(73)	TFCFP	(31)	TFCons	2
(73)	TFCFP	(7)	TTC	2
(31)	TFCons	(32)	TEngCons	2
(76)	TFCP	(91)	TCFCP	2
(76)	TFCP	(31)	TFCons	2
(74)	TFCRM	(31)	TFCons	2
(74)	TFCRM	(7)	TTC	2
(1)	TFI	(97)	ATL	2
(1)	TFI	(102)	FW	2
(1)	TFI	(58)	TCO2EII	2
(1)	TFI	(57)	TGHGEII	2
(1)	TFI	(109)	TIC	2
(1)	TFI	(93)	TPS	2
(1)	TFI	(28)	TRI	2
(1)	TFI	(98)	TSICI	2

Table A5. *Cont.*

Source		End		Relationship Weight
n°	*Acronym*	n°	*Acronym*	
(1)	TFI	(44)	TTechI	2
(1)	TFI	(59)	TTEII	2
(57)	TGHGEII	(30)	TGHGESC	2
(57)	TGHGEII	(59)	TTEII	2
(78)	TGHGEP	(30)	TGHGESC	2
(78)	TGHGEP	(89)	TTEP	2
(54)	TGHGERM	(30)	TGHGESC	2
(54)	TGHGERM	(107)	TTERM	2
(30)	TGHGESC	(77)	CO2Foot	2
(79)	TGHGET	(30)	TGHGESC	2
(79)	TGHGET	(42)	TTETransp	2
(62)	TGHGEW	(30)	TGHGESC	2
(62)	TGHGEW	(63)	TTEW	2
(66)	TGHGEWW	(30)	TGHGESC	2
(66)	TGHGEWW	(67)	TTEWW	2
(84)	TGWF	(112)	WFootC	2
(71)	THI	(27)	TSW	2
(38)	THM	(22)	TSI	2
(109)	TIC	(3)	TICU	2
(3)	TICU	(27)	TSW	2
(51)	TIFS	(22)	TSI	2
(96)	TII	(16-47)	NPV	2
(96)	TII	(17)	ROI	2
(95)	TIILC	(96)	TII	2
(45)	TITI	(96)	TII	2
(94)	TIU	(45)	TITI	2
(18)	TJC	(19)	TJI	2
(19)	TJI	(22)	TSI	2
(8)	TLC	(14)	TC	2
(9)	TMC	(14)	TC	2
(2)	TP	(3)	TICU	2
(2)	TP	(46)	TPIT	2
(55)	TPbyT	(75)	EngBal	2
(55)	TPbyT	(106)	PCDS	2
(55)	TPbyT	(2)	TP	2
(55)	TPbyT	(50)	TQP	2
(55)	TPbyT	(4)	TRev	2
(10)	TPC	(14)	TC	2
(20)	TPLA	(21)	TDL	2

Table A5. *Cont.*

Source		End		Relationship Weight
n°	*Acronym*	n°	*Acronym*	
(93)	TPS	(49)	TGE	2
(93)	TPS	(96)	TII	2
(50)	TQP	(26)	TCSat	2
	TR	(55)	TPbyT	1.5
(4)	TRev	(5)	TaxP	2
(4)	TRev	(15)	TBEB	2
(28)	TRI	(22)	TSI	2
(52)	TRW	(53)	TCO2ERM	2
(52)	TRW	(83)	TCRMA	2
(52)	TRW	(90)	TECRM	2
(52)	TRW	(54)	TGHGERM	2
(52)	TRW	(51)	TIFS	2
(52)	TRW	(55)	TPbyT	2
(52)	TRW	(36)	TRMSS	2
(52)	TRW	(33)	TSRW	2
(52)	TRW	(107)	TTERM	2
(52)	TRW	(103)	VWI	2
	TS	(104)	ADTC	1.5
(22)	TSI	(27)	TSW	2
(101)	TSIC	(22)	TSI	2
(99)	TSICC	(101)	TSIC	2
(98)	TSICI	(101)	TSIC	2
(100)	TSICS	(101)	TSIC	2
(7)	TTC	(8)	TLC	2
(44)	TTechI	(96)	TII	2
(59)	TTEII	(60)	TEII	2
(59)	TTEII	(12)	TEmCost	2
(59)	TTEII	(41)	TTESC	2
(89)	TTEP	(82)	TEIP	2
(89)	TTEP	(12)	TEmCost	2
(89)	TTEP	(41)	TTESC	2
(107)	TTERM	(56)	TEIRM	2
(107)	TTERM	(12)	TEmCost	2
(107)	TTERM	(41)	TTESC	2
(42)	TTETransp	(88)	TEIT	2
(42)	TTETransp	(12)	TEmCost	2
(42)	TTETransp	(41)	TTESC	2
(63)	TTEW	(65)	TEIW	2
(63)	TTEW	(41)	TTESC	2

Table A5. *Cont.*

Source		End		Relationship Weight
n°	***Acronym***	**n°**	***Acronym***	
(67)	TTEWW	(69)	TEIWW	2
(67)	TTEWW	(41)	TTESC	2
	TV	(92)	TF	1.5
(11)	TWC	(13)	TEnvCost	2
(40)	TWRec	(110)	TEIAvoidWRec	2
(111)	UnIn	(96)	TII	2
	UnTLF	(111)	UnIn	1.5
(103)	VWI	(18)	TJC	2
	WConsF	(34)	TAWC	1.5
	WCostF	(86)	TCWC	1.5
	WCTF	(102)	FW	1.5
(112)	WFootC	(61)	TEI	2
	WfootF	(112)	WFootC	1.5
	WPF	(37)	TAW	1.5
	WRecEIF	(110)	TEIAvoidWRec	1.5
	WRF	(39)	TARW	1.5
	WRMCTF	(103)	VWI	1.5
	WRRMF	(40)	TWRec	1.5
	WWPF	(35)	TAWW	1.5

Appendix C. Metric Hierarchization for Selection

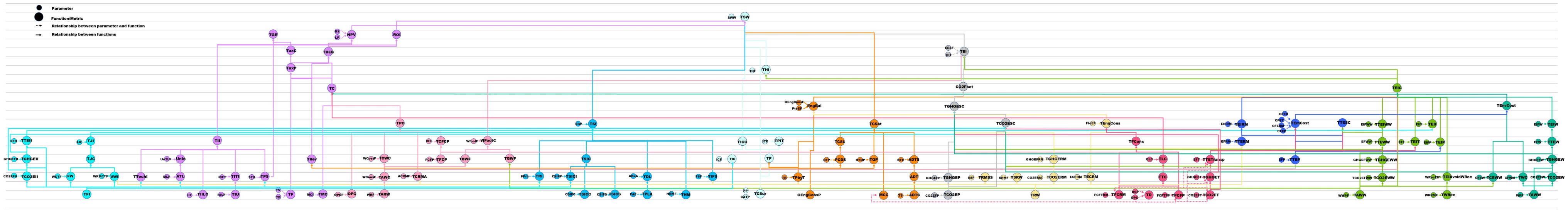

Figure A2. Metric relationship by clusters.

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