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Sustainability as a Multi-criteria Concept

New Developments and Applications

Edited by
Luis Diaz-Balteiro, Jacinto González-Pachón and Carlos Romero

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About the Editors

Luis Diaz-Balteiro is a Full Professor of Forest Management at the Technical University of Madrid and is responsible for the Research Group "Economics for a Sustainable Environment". He is the author or co-author of 65 papers published in Journals included in ISI WOS. His h-index is 19, with more than 1400 citations in ISI WOS. Moreover, he is the author /co-author of 7 books and 17 book chapters, 8 of which are published in international publications; he has also supervised 7 doctoral theses. He is Section Editor-in-Chief of the journal Forests. He has reviewed more than 200 JCR papers belonging to 74 different Journals. In short, his research has focused on the design and application of different analytical tools for the resolution of problems associated with forest management and forest economics issues.

Jacinto González-Pachón is an Associate Professor in the Department of Artificial Intelligence at Universidad Politécnica de Madrid (UPM). He holds a B.S in Mathematics and a PhD in Computer Science. His teaching and research specialities are in the field of Preference Modelling and Rational Choice, Multi-Criteria Decision-Making Problems, Group Decision-Making Problems and Conflicts Resolution. He is the author of papers that have appeared in international refereed journals and monographs such as *Computers and Operation Research*, *European Journal of Operational Research*, *Journal of the Operational Research Society*, Lecture Note in *Economics and Mathematical Systems, OMEGA, Theory and Decision* and others.

Carlos Romero is Emeritus Professor of Economics at the Technical University of Madrid where he founded the Research Group "Economics for a Sustainable Environment". He is author, co-author or co-editor of 23 books and 204 papers. His research impact according to ISI "Core Collection" presents an h index of 32 with around 3200 citations and an h index of 34 with more than 4100 citations according to ISI "All Data Bases". In Google Scholar his h index is 49 with more than 11,200 citations. He was Guest Co-editor of Special Issues of *Agricultural Systems* (1993), *Annals of Operations Research* (2000, 2016), *International Transactions in Operational Researc*h (2018), *Journal of the Operational Research Societ*y (2018) and the *Journal of Sustainability* (2020). Among his current editorial positions, he is Area Editor (multi-objective optimisation and goal programming) of the *Journal of Multi-Criteria Decision Analysis*, Associate Editor of Forest Science and Member of the Editorial Board of Operational Research. Among other distinctions, he received the National Prize of Economics and the Environment in 2001 and in 2006 he was awarded the Georg Cantor Award bestowed by the International Society on Multiple Criteria Decision Making. He is a selected Fellow of the Operational Research Society. He was a Member of the Executive Committee of the International Society on Multiple Criteria Decision Making.

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Editorial

Sustainability as a Multi-Criteria Concept: New Developments and Applications

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The sustainable management of the environment and its embedded resources is one of the most important, if not the major challenge of the 21st century, which demands from current science and technology the development of a scientifically sound conceptual framework that is implementable from an operational point of view for properly tackling this important and complex topic. Although important steps have been taken in the right direction, nowadays, this type of theoretical framework is far from being fully achieved or, especially, accepted by the several institutions forming the current democratic societies. In our view, this theoretical framework should be supported by a plurality of scientific theories which implies the convergence of knowledge flowing from many disciplinarian fields like computational sciences, ecology, economics, mathematics, sociology, etc. This convergence of disciplines, plus its necessary social acceptance, makes its setting highly challenging.

To go deeper into the difficulties associated with the above challenge, it might be useful to distinguish between what could be called the "old" and "new" sustainability. To address this task, it makes sense to trace the origins of the idea of sustainability and analyse how this concept has evolved to its current form. In this sense, we should be aware that the idea of sustainability was born at the beginning of the 18th century in the field of forestry by von Carlowitz [1]. This illustrious German nobleman defined a sustainable forest plan as the one which could provide a long-term stable supply of a flow of timber and timber-linked products (e.g., fruits, firewood, etc.) indispensable for the welfare of human beings. In other words, this classic or "old" view of sustainability was conceptualized from a mono-functionality perspective. This approach was similarly applied later on, to other natural resources, and the term gained visibility after its massive implementation in the environmental domain [2]. Within this framework, the necessary and sufficient condition for the sustainable management of a resource is analytically very straightforward: "the use rate must be less than the rate of biological regeneration of the specific resource studied". Maintaining this condition would guarantee the future sustainable management of the resource.

It is important to note that this type of approach implicitly assumes the view that economic systems interact with the environment in a way which, nowadays, could be considered unrealistic. In fact, within this orientation, it is accepted that the environment provides two basic functions for economic activity: first, sources of raw materials to be used as inputs for the different production processes and, second, the assimilation of all the waste generated by those production and consumption processes. Moreover, in this old approach to sustainability, it is implicitly assumed that the environment has a practically infinite capacity to sustain those two basic functions: a source of inputs and a sink for waste. In other words, this view of sustainability has been established within what is called a linear model, linking the environment and the economic systems.

This theoretical and operational approach has worked well for many years, proving to be very fertile for establishing rational guidelines geared towards an efficient use of the environment and its embedded resources. In the last quarter of the 20th century, this theoretical orientation was well established in the economics field with the publication of several seminal and pioneer textbooks, forming what is known now as the environmental economics discipline.

It is important to insist on the fact that the above conceptualization of sustainability worked well until the end of the 20th century. Around this period of time, this type of approach became insufficient for two reasons. First, the assumed almost infinite capacity of the environment as a source of inputs and as a sink for waste was refuted by the reality. Thus, the mindset of modern societies changed, and the environment was considered scarce in the above two capacities. To be more specific, it was recognized that the environment had physical limits, and that it would be necessary to optimize this type of scarcity. Second, modern societies started to demand multiple goods and services from the environment and its embedded resources. For some of them there are no markets and, consequently, they have no exchange value or price; however, their optimal provision is essential to the welfare of society.

In order to illustrate the above ideas, let us consider, for instance, the case of forestry systems. Although the sustainability concept in forestry changed between the seventeenth and nineteenth centuries, for this type of system societies nowadays demand not only a long-term stable flow of timber products as were required by the old sustainability, but also an stable provision of basic essential environmental goods and services (e.g., to reduce soil erosion, biodiversity conservation, carbon sequestration, etc.). The explicit consideration of a multiplicity of functions of very different natures underlying the management of the environment and its embedded resources makes the old concept of sustainability clearly insufficient and requiring changes and extensions.

On the other hand, the explicit recognition of the finitude of the environment as well as of the multi-functionality issue are not the only reasons justifying a new view of the concept of sustainability and the corresponding changes in the theoretical framework which underpin its efficient management. In fact, democratic societies demand social participation in the acceptance of the different policies related to the different aspects of sustainable environment management. In short, this crucial issue should be dealt with from the perspective of a participatory decision-making process. For an illustrative example of this type of orientation, see the case of the real urban forest planning problem in Sweden [3].

Briefly, it can be stated that any theoretical framework able to accommodate the above concerns and critical issues and, consequently, characterizing the so-called new sustainability, will require, first, to take into consideration in quantifiable terms the multiplicity of functions associated nowadays with the environment, and, second, to incorporate into it, in one way or another, the manner in which different segments of society or the stakeholders perceive the relative importance of these functions.

A possible first step towards facing up to the above challenges and to correctly performing a sustainable management of the environment and its embedded resources would consist of resorting to the so called "indicator approach" [4,5]. According to this approach, the sustainability of a system is characterized by a battery of indicators of different natures. In many instances, these indicators are grouped into three pillars of an economic, environmental and social nature, respectively. Once the indicators and pillars have been defined, the next step consists of an aggregation process of the indicators in order to obtain a final composite index whose value is considered to be a proxy of the degree of sustainability of the system studied.

With this orientation in mind, a crucial task will be to establish a sound and pragmatic procedure for undertaking the above-mentioned aggregation procedure. In this Special Issue, and supported by recent, extensive literature, it is postulated that the most promising and fertile procedure would be to link the concept of an indicator with that of a criterion as it is used within the multi-criteria decision making (MCDM) theory. In this way, all the concepts and techniques of this well-known and widely used theory could underpin a fertile framework for dealing with the so-called new sustainability. Thus, it is important to recall that the main purpose of the MCDM theory consists of proposing sound methods for aggregating criteria (objectives, goals, attributes) in conflict. In this way, compromises among the criteria considered with a clear preferential interpretation are obtained [6,7]. In the last ten years or so, practically all the methods within the MCDM theory, with their particular merits and flaws, have been applied for solving different problems associated with sustainable environment management. This issue has been illustrated in some critical reviews [8]. These embryonic ideas would seem to be a promising outline for building a theoretically sound and computationally efficient framework for addressing these types of problems.

In keeping with these ideas, this Special Issue of *Sustainability* aims to take a step in the direction of linking the conceptualization and measurement of the degree of sustainability of a natural system with the MCDM theory. Thus, we present a collection of ten papers dealing with recent theoretical and applied issues of the so-called new sustainability within the MCDM framework. We hope that this material will reinforce this type of orientation.

The origin of this volume was a kind invitation made by the Editors of *Sustainability* to organize a Special Issue with this orientation. A call for papers was announced, calling for submissions dealing with theoretical as well as applied aspects of sustainability, understood as a multi-criteria concepts. After a thorough blind review process, ten papers were finally accepted.

As is well known, characterizing and measuring the sustainability of a specific natural system has been the focus of research in many scientific fields, in many cases by resorting to several multi-criteria decision making approaches. This pluridisciplinary perspective is present in the ten papers which form this Special Issue. We have ordered the papers into five blocks according to the area of application. The first block is devoted to the energy planning area and comprises two papers. The first one, by Papapostolou et al. [9], deals with problems related with the potential decarbonisation of the countries forming the European Union. In this way, several alternatives are evaluated by resorting to the Preference Ranking Organisation Method for Enrichment Evaluation (PROMETHEE) method within a fuzzy context. The second paper in this block, by dos Santos Martin et al. [10], deals with the determination of the optimal combination of wind and thermal energy units. The authors apply a hybrid approach combining goal programming with the progressive bound constraint method.

The second block comprises two papers dedicated to agricultural issues. Thus, Segura et al. [11] deal with the problem of sustainability for a supplier evaluation within a food supply chain management perspective. The authors resort to Multi-Attribute Utility Theory (MAUT) and PROMETHEE methods. The other paper in this block, by Gómez-Limón et al. [12], proposes a new composite indicator for measuring environmental sustainability at the farm level by resorting, with a comparative purpose, to three different weighting methods.

The third block comprises papers devoted to the analysis of different issues related with the sustainable management of the environment and its embedded resources. Thus, Ezquerro at al. [13] deal with a sustainable forest management problem in a Spanish forest. The authors propose a lexicographic goal-programming model with two priority levels grouping six goals of economic as well as environmental nature. Barinaga-Rementeria and Etxano [14] address the debate regarding weak versus strong sustainability in the field of rural land use planning. The authors deal with a specific case study in the Basque Country (Spain), implementing a social multi-criteria evaluation by resorting to an outranking orientation.

The fourth block groups two papers that explore the measurement of sustainability at the aggregate level of the countries forming the European Union. In the paper by Garcia-Bernabeu et al. [15], a circular economy composite index is proposed, in order to benchmark the European Union countries' performance. To achieve this purpose, the authors resort to the Technique for Order Preferences by Similarity to Ideal Solutions (TOPSIS) methodology. In the second paper of this block, Stanujkic et al. [16] provide a ranking of these European countries, adopting the Sustainable Development Goals considered in the "Agenda 2030". The authors combine compromise multi-criteria distance function models with Shannon entropy methods.

The last block comprises two papers combining case studies for dealing with different environmental issues. Thus, André et al. [17] address a problem related to the adoption of an environmental certification in Costa Rica. To achieve this purpose, the authors resort to the Analytic

Hierarchy Process (AHP) approach. Finally, Babalola [18] addresses the problem of the sustainable management of home biodegradable waste. In this way, the author presents a case study in Japan, defining and ranking different lines of treatment of the waste by resorting again to the AHP approach.

It is important to remark upon the ample variety of MCDM techniques employed in dealing with the problems analysed in all the papers. Thus, the reader can find applications using PROMETHEE, several variants of goal programming, MAUT, TOPSIS, Combined Compromise Solutions, etc. The very different nature and great social interest in the sustainable problems presented are also remarkable. At any rate, we hope that this material will encourage academic and practitioners to orientate their future research towards this hot and vital topic.

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Article

Supporting Europe's Energy Policy Towards a Decarbonised Energy System: A Comparative Assessment

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Abstract: The European Union (EU) aims to prepare its strategy and infrastructure for further decarbonisation of its energy system in the longer term towards 2050. Recent political discussions and research interest focus on ways to accelerate the development and deployment of low-carbon technologies with respect to the targets set for 2030 and 2050. However, the diverse options available that are to be implemented, are policy sensitive and need careful comparative assessment. This paper presents a multi-criteria approach based on an extension of the Preference Ranking Organization METHod for Enrichment of Evaluations (PROMETHEE) method for group decision-making that incorporates fuzzy set theory in order to evaluate alternative transformation pathways for achieving a sustainable energy system in EU. This assessment aims at providing a direction towards a most preferable pathway concept that should be taken into account by a future model-based analysis of the necessary transformation of our energy sector. The results obtained could support policymakers in drawing effective recommendations based on the findings. The added value of this analysis to policymakers is its contribution to plan climate and energy strategies towards a low-carbon transition pathway by using the information of this approach and prioritizing uncertainties through an environmental and energy perspective.

Keywords: climate and energy policy; transformation pathways; low carbon technologies; decision support; multi-criteria analysis; fuzzy PROMETHEE

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1. Introduction

In these days, as the impact of climate change becomes more and more prevailing, formulation of mitigation policies has become a high priority on Europe's political agenda. Through the "2030 Climate and Energy Policy Framework", more binding targets were defined for 2030 requiring: at least 40% cuts in greenhouse gas emissions (from 1990 levels), at least 27% share for renewable energy and at least 27% improvement in energy efficiency [1], while recently the European Parliament approved binding 2030 target for renewables (32%) and an indicative target on energy efficiency (32.5%) that will play a crucial role in meeting the European Union's (EU) climate goals [2]. For the more distant future, based on the EU Energy Roadmap 2050 the focus lies in four main decarbonisation routes for the energy sector, which are mainly focused on: energy efficiency measures, renewable energy sources (RES), nuclear and carbon, capture and storage (CCS) [3]. The EU is now on a path towards a low carbon economy by 2050, to ensure regulatory certainty and a sustainable energy future [4]. In this concept and in order to promote technology in EU's energy and climate policies, the Strategic Energy Technology Plan (SET-Plan) was designed in 2008 [5]. Since then, it has been EU's key pillar to address the challenge of accelerating the development of low-carbon technologies, which ultimately aims at widespread adoption by the market.

Although targets are well defined, extensive uncertainties exist in the European energy future necessitating the identification and analysis the parameters affecting the proposed decarbonisation options. Scenarios are a widely used tool for analysing the unknown future and they have been widely exploited in the field of climate change adaptation and policy [6,7]. Scenarios are defined as "alternative images of how the future might unfold" [8] or in other words, "plausible descriptions of how the future might evolve, based on a coherent and internally consistent set of assumptions ('scenario logic') about the key relationships and driving forces" [9]. Literature review greatly manifests that there is a variety of perspectives regarding critical uncertainties affecting the energy future. Ghanadan and Koomey (2005) [10] in their publication underline five major driving forces, namely the relevance of energy diversity, relative attention to oil and transportation, long-term prominence of energy and security, types of clean energy activities, and role of distributed generation, while Kowalski et al. (2009) [11] differentiates scenarios based on the technologies exploited. Brown et al. (2001) [12] use the levels of action or cost of each policy as guidelines to develop policy scenarios. Raskin et al. (2010) [13] first consider the extent to which scenarios emerge from the turbulence of the present or emerge gradually as evolutionary futures and second, they assess the prioritization of sustainable development. Through scenario formulation Riahi et al. (2012) [14] put more emphasis on energy efficiency and demand-side transformation, and they name three key uncertainties: the level of energy demand, fuels and technologies in the transportation section, and differentiation of portfolio option from supply-side.

Using as a compass the principle that the objective of using scenarios is not to predict the future, but to better understand uncertainties in order to reach decisions that are robust under a wide range of possible futures [15], this paper focuses on two critical uncertainties in order, not to forecast the state of the global energy system by the year 2050, but rather bound the range of plausible alternative futures by defining certain trajectories that could significantly affect decarbonisation policy in the years to come. More precisely, in this analysis the widely-used 2x2 scenario typology adopted so as to combine two main dimensions of uncertainty into four storylines spanning a wide possibility space. Figure 1 indicates the scenario topology that varies two critical uncertainties: decentralisation vs. path dependency (x-axis); and cooperation vs. entrenchment (y-axis). On the x-axis is the degree of decentralization that focuses on whether variation and experimentation of energy policies is being pursued or whether minimal switching and transitional costs are sought. On the y-axis is the degree of European cooperation that explores whether there is centralized coordination or control at national level. These two dimensions of uncertainty create a possibility space that could be explored by the four contrasting storylines that generate four different transformation pathways, the key characteristics of which will be presented in the following study.

This paper analyses the aforementioned transformation pathways on the basis of a set of relevant criteria aiming at revealing the one with the most auspicious prospects of succeeding and achieving energy sustainability in EU. To deal with the disparate preferences of decision-makers, as well as to manage the uncertainty that arises when solving decision problems, a methodological assessment framework is developed using the multi-criteria Fuzzy Preference Ranking Organization METHod for Enrichment of Evaluations (PROMETHEE) method, which combines the principles of multi-criteria decision analysis and fuzzy logic. The results provide a clear picture of the preferred options and their interactions with the evaluation criteria, while the conclusions can significantly contribute to energy and climate policy-making in the energy sector.

Due to its ability to deal with ranking of many alternatives based on conflicting criteria, multi-criteria analysis has been one of the very fast-growing areas of Operational Research during the two last decades, with applications in various areas of human activity [16]. Many strategic environmental and energy planning issues have been analysed based on multi-criteria decision-making (MCDM) methods [17–26] and especially the use of PROMETHEE method has concentrated great interest as it becomes apparent after an extensive literature review [27–35].

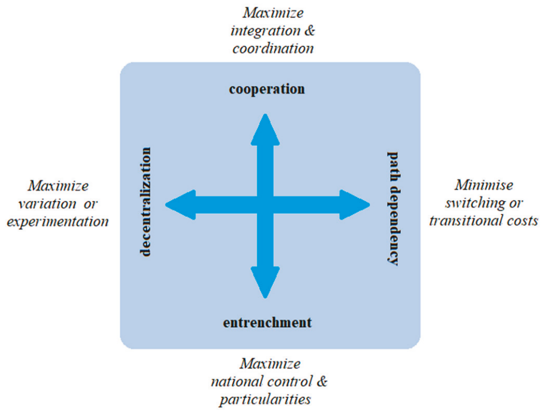

Figure 1. Proposed 2 × 2 scenario topology.

In order to meet specific requirements when uncertain and imprecise knowledge, as well as possibly vague preferences have to be considered [36], fuzzy set theory is integrated in the proposed methodological framework. From 2000 to 2017, fuzzy PROMETHEE has been exploited in at least twenty-five publications [37] and according to Kahraman et al. (2015) [38] some of the most impactful articles tackle problems in the environmental management field [39–41]. Making use of the popularity and suitability of fuzzy PROMETHEE in managing energy sector problems and the restricted number of fuzzy PROMETHEE publications for evaluating different energy futures, this study offers an original work able to shed light in the policy-making problem related to sustainable transition. To the best of our knowledge, however, this is the first fuzzy-PROMETHEE-based MCDM technique for group decision-making developed for ranking transformation pathways for achieving a sustainable European energy future. In doing so, we attempt to extend the application domains of the fuzzy PROMETHEE method. The added value of this analysis to policymakers is its contribution to plan climate and energy strategies towards a low-carbon transition pathway by using the information of this approach and prioritizing uncertainties through an environmental and energy perspective.

Following this introductory section, the remainder of the paper is structured as follows: The second section provides an overview of the material and methods that were followed for the comparative assessment of the transformation pathways towards a decarbonised energy system. It starts with an overview of the methodological approach that were followed. In the Problem formulation subsection, the alternative transformation pathways are elaborated and the evaluation criteria are presented. In the next subsection, the appropriate MCDM method is selected after an extended review in the field of multi-criteria analysis and energy policy planning. The choice of method is justified, fuzzy set theory is presented briefly and the main steps for implementing the fuzzy PROMETHEE are described. Subsequently, the methodology is applied in the Results section and the produced output is analysed in the Discussion section. Finally, in the Conclusions section, the main conclusions are summarized and key points are proposed for further research.

2. Materials and Methods

2.1. Overview of the Methodological Approach

The following Figure illustrates the methodology applied to assess the suitability and effectiveness of alternative transformation pathways to achieve the transition towards a sustainable European energy future (Figure 2).

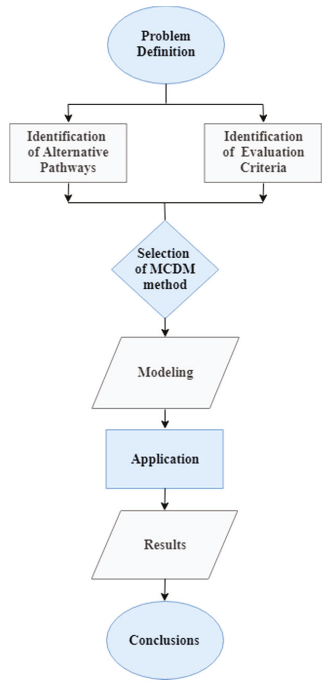

Figure 2. Overview of the methodological approach.

The first step was the definition of the problem, which involved the identification of alternative transformation pathways, which reflect different sustainable trajectories for the European energy future, and identification of criteria for their evaluation (Section 2.2). Subsequently, after taking into consideration the specific characteristics of the problem under study and the corresponding literature (Sections 2.3.1–2.3.3), and after a detailed comparison among the MCDM methods (Section 2.3.4), the most appropriate MCDM method was selected. This MCDM method was applied to compare and rank the alternatives from the most to the least preferable according to decision-makers' value system. Therefore, after gathering all necessary information about pathways' ratings and defining method's parameters, the selected MCDM algorithm was executed multiple times for sensitivity analysis purposes (Section 2.3.5). Finally, the resulting rankings were analysed providing valuable insight regarding the most suitable pathways for achieving decarbonisation in EU (Sections 4 and 5).

2.2. *Problem Formulation*

2.2.1. Alternative Transformation Pathways

First, alternative transformation pathways for achieving a sustainable transformation of the EU energy system are defined. The pathways formulation is based on research conducted within the framework of the "SET-Nav - Navigating the Roadmap for Clean, Secure and Efficient Energy Innovation" project (http://set-nav.eu/). The four narratives presented below stem from the 2x2 topology described in Introduction and they are formulated with the aim to answer questions regarding: (a) driver questions related on '*why*' the pathway scenario happens and (b) elements questions highlighting '*what happens*' with focus on the outcome of the pathways [42]. Their key characteristics are described in this section and Figure 3 summarizes schematically the four alternatives.

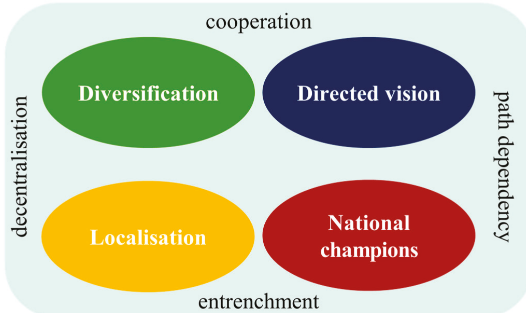

Figure 3. Transformation pathways at a glance [42].

A_1—Diversification**.** This pathway describes a decentralizing trajectory for the EU energy system in the context of cross-border cooperation and integration. This signals the entry of new, heterogeneous actors, challenging the dominance of centralised asset-owners and incumbent service-providers. Open digital platforms become essential for coordinating the activity of this diversified energy economy, facilitated by regulatory experimentation and opening. This provides a positive environment to foster interaction among heterogeneous actors across countries. Active involvement of consumers and developments in digitalization allows smart grid technologies to thrive as well as to setup opportunities for new entrants and innovation. In this pathway, renewable energies, smart grids and electrical vehicles are the driving force behind decarbonisation. Countries have cooperative attitudes towards regulatory opening and promoting new business models. This path requires cooperation between countries on technological progress, diversification of flexibility options for balancing RES and modest expansion of interconnected electricity grid capacity.

A_2—Directed Vision**.** This storyline defines a path-dependent trajectory for the EU energy system that is directed by the Commission's vision set out above for an ever-closer energy union. The EU together with stakeholders (able to operate at an EU level) is guided by strong and shared expectations for future goals and current directions of travel. This broad buy-in becomes enshrined in stable policy frameworks which are coordinated between member states to ensure a consistent European-wide playing field. For this pathway cooperation is expected between member states on technological progress matters. Within this pathway we expect a balanced mix in energy supply, comprising new nuclear fleet (but no prolongation of the existing one), CCS and renewables with focus on centralised solutions as key pillars. A diversification comes into play for flexibility options to facilitate RES integration but with prioritisation of centralised solutions. Concerning infrastructure, we expect a strong expansion in grid capacity whereas energy efficiency remains as no regret option.

A_3—National Champions**.** This pathway defines a path-dependent EU in which historical incumbency and national interests play a stronger guiding hand. This continuity in development minimises transitional risks and costs, at least in the near-term. Incumbent firms and organisations, including current or former national monopolies, play a leading role particularly in the design, finance, construction and operation of large-scale energy infrastructure. This pathway assumes a focus on national preferences, using available resources and prioritising tailored solutions according to national needs. Incumbents in the energy sector have a decisive role in defining national policy priorities. The focus on what is there nationally/locally leads in energy supply to the prolongation of the operational times of nuclear (existing fleet) that goes hand in hand with the built-up of new capacities, CCS plays a strong role, and (centralised) renewables contribute depending on their local availability. Grid expansion is moderate and energy efficiency remains as no regret option.

A_4—Localisation. This storyline describes how the decentralising forces observable today in the EU start to chip away more forcefully at the centralised infrastructures, firms, and regulatory environments, but with marked national and local variation. Member states seek to maximise their use of locally-available resources, giving rise to differentiated energy strategies and policy frameworks across the EU. Resistance to pan-European infrastructure and integration projects opens up space for smaller-scale experimentation and diversity. Digitalisation again becomes essential for supporting coordination and effective system management, but with an emphasis on national competitive advantage in the returns to scale of a dominant platform. In accordance with above-mentioned, there is a clear focus on local resources and solutions. Moreover, there is a clear ban for large scale international cooperation, being on regulation as well as on infrastructure (grids). That puts in practice a limit for centralised supply solutions, with only exceptions possible at country level. The focus on what is there nationally/locally available leads to the prolongation of the operational times of the existing nuclear fleet, while CCS may play a role locally and renewables contribute depending on their local availability with a tendency towards decentral/local options due to the lack of grid interconnection. Grid expansion is very limited and energy efficiency remains as no regret option.

It is crucial to underline that these short descriptions highlight only the most salient features that support separate the storylines from one another. Interpreting each storyline is not an exact science. However, it is essential that the interpretive detail of each storyline is internally consistent (avoiding tensions or contradictions), comprehensive (covers all relevant drivers and dynamics), and coherent (adds up to a meaningful whole).

2.2.2. Evaluation Criteria

The existence of different possible trajectories for the European energy future necessitates their comparative assessment based on a well-defined and representative set of criteria in order to distinguish the most propitious one. Given the available pathway narratives, the following four criteria were defined with a view to capture and encompass all key features of the alternatives into the evaluation process. It is worth mentioning that the definition process of the of the assessment criteria, as well as their final section were assisted and validated by the integration of experts' insights and opinions, harvested through a participatory process [43]. This process was elaborated through a series of bilateral meetings with stakeholders and facilitated by the implementation of topical and modelling workshops with the framework of the EU Horizon2020 SET-Nav project, fostering dialogue in order to gain useful feedback on the most suitable criteria.

<u>C_1—Regulatory Framework.</u> This criterion assesses the adequacy of the regulatory framework to support and ensure the implementation of the actions and policies proposed by each path. The more relaxed the legislative framework, the greater the risk of failure in the implementation of the planned policies, and the more amendments it requires, the more difficult it becomes to implement [44].

<u>C_2—Compatibility with Market.</u> Given that Europe has a mature market, it is important to assess the extent to which each pathway is compatible with the current situation or if it opposes it because its actions involve changes in consumer behaviour and the role of the participating companies in energy market, thus leading to a change in demand and price equilibrium. In the light of this criterion, the pathways requiring a mature market are more preferable due to their easier application in the present mature environment, while the rest are considered more prone to risk as they require significant changes [45,46].

<u>C_3—Compliance with SET-Plan.</u> This criterion reflects the extent to which each pathway achieves the goals of SET-Plan and evaluates its ease of implementation. Ease of implementation lies in the volume of new infrastructures and technologies included paths. The more complex and innovative policies are, the more difficult it is to implement them, since they deviate from the existing reality and therefore have a greater risk of failure [5].

<u>C_4—Stakeholder Awareness.</u> This criterion assesses the extent to which those involved in each path are aware of climate change issues and are actively taking action to combat it. The term "stakeholders" refers to the European Union, the Member States, associated enterprises and the society. The greater the familiarity with greenhouse gas reduction mechanisms, the more auspicious the prospects for the success of the actions each pathway proposes [47].

2.3. Selection of the MCDM Method

2.3.1. The PROMETHEE Method

According to Siskos (2008) [48], the difficulty or the complexity of a decision problem should be sought mainly in two factors: firstly, to the multidimensional character of the alternatives' consequences and secondly, to the uncertainty that governs the problem's data. The methodological framework that is widely used to tackle such problems is offered by MCDM approaches. Apart from their obvious ability to handle numerous criteria, these methods also facilitate the decision-maker to better understand the problem's nature and prioritize criteria, and hence they promote decision-makers' active engagement with the process and support collective decision-making [26]. Hence, the transformation pathways evaluation problem clearly belongs to the category of such complex problems which calls for a multi-criteria approach.

In this study, the PROMETHEE method was selected due to its simplicity and its capacity to approximate the way human mind expresses and synthesizes preferences in front of multiple contradictory decision perspectives [49]. The PROMETHEE it was initially developed by Brans in 1982 [50], further extended by Vincke & Brans (1985) [51] and belongs to the family of MCDM methods that rely on the outranking relations theory. It is based on pairwise comparisons between two alternative choices in order to determine partial binary relations denoting the strength of preference of an alternative A over alternative B, and the final ranking results from taking into account the degree of superiority (Leaving Flow) and inferiority (Entering Flow) that each alternative has compared to the others.

The PROMETHEE family of outranking methods includes the PROMETHEE I for partial ranking of the alternatives and the PROMETHEE II for complete ranking of the alternatives. There are also several alternative versions of the PROMETHEE methods, such as the PROMETHEE III for ranking based on interval, the PROMETHEE IV for complete or partial ranking of the alternatives when the set of viable solutions is continuous, the PROMETHEE V for problems with segmentation constraints [52], the PROMETHEE VI for the human brain representation [53] and the PROMETHEE Group Decision Support System (GDSS) for group decision-making [54].

When comparing different outranking methods, PROMETHEE stands out due to its fairly simple design, ease of computation and application and stability of results [35]. Some of the main advantages that the PROMETHEE method offers is that compensations between criteria can be controlled, less effort is required from the decision-makers for preference modelling, while the process enables them to stay closer to the actual decision problem. Apart from the methodological advantages, real life observations show that decision-makers are often not fully aware of their preferences, or that they are not able to express these in an unambiguous way without appropriate support and PROMETHEE method can provide this [35]. The advantage of the partial ranking of PROMETHEE I is that some bad performing alternatives can be excluded from the further evaluation exercises, with the consequence that the data requirement is reduced [55], while the complete ranking of PROMETHEE II is useful to supply to the decision-maker information on how the final ranking changes when different decisions on weights, criteria and aggregation procedures are taken [56]. PROMETHEE can simultaneously deal with qualitative and quantitative criteria, criteria scores can be expressed in their own units, while it can deal with uncertain and fuzzy information. Apart from the above-mentioned advantages and the recognition of the method, the selection of PROMETHEE was also stimulated by the availability of its methodological extensions in the fuzzy environment, facilitating the prospective enhancement of the tool, as well as its capacity to effectively tackle the problematic of interest, which is ranking the alternatives. According to Gavade (2014) [57], a limitation of PROMETHEE is that suffers from the rank reversal problem when a new alternative is introduced while, in the case of many criteria and options, it may become difficult for the decision-maker to obtain a clear view of the problem and to evaluate the results. However, this drawback does not affect the present problem since the number of the criteria and alternatives are limited.

2.3.2. Literature Review on PROMETHEE and Energy Policy

The MCDM methods of PROMETHEE family, as well as combination of the PROMETHEE with other MCDM techniques have been extensively applied to support decision-making processes for issues related to the energy policy, management and planning. Strantzali et al. (2017) [58] uses a multi-criteria decision-making model based on PROMETHEE II, to determine the best fuel mix for electricity generation in an isolated Greek island, having determined a set of 7 energy policy scenarios that are assessed against economic, technical, environmental and social criteria. The energy policy scenarios include the use of conventional fuels, wind energy and natural gas, in its liquid form, liquefied natural gas (LNG). A combination of the PROMETHEE method with the AHP was used by Turcksin et al. (2011) [59] to recommend a multi-instrumentality policy package to the Belgian government in its objective to reduce environmental externalities by encouraging people to make a more sustainable vehicle choice. Through PROMETHEE II Diakoulaki et al. (2007) [60] investigated the prospects for the exploitation of the Kyoto Protocol's Clean Development Mechanism (CDM) in Greece. The most promising types of CDM projects were evaluated in 5 selected host-countries in terms of technical experience, duration of project realization, legislative framework, political compatibility and emission reduction potential. In the same year Diakoulaki & Karangelis (2007) [61] employed PROMETHHE, based on economical, technical, and environmental criteria, to comparatively evaluate four scenarios for the development of the power generation sector in Greece. Doukas et al. (2006) [62] applied PROMETHEE II to evaluate the sustainable technologies for electricity generation, according to the environmental, social, economic, and technological dimension of sustainable development. Madlener et al. (2007) [63] used PROMETHEE algorithm to assess five renewable energy scenarios considered refer to Austria in the year 2020. The innovative methodology applied, examined possible energy futures paths by combining scenario development; multi-criteria evaluation; and a participatory process with stakeholders and energy experts on the national level.

Table 1 includes a variety of studies using PROMETHEE in energy related fields and environmental management [28,64,65].

Table 1. Literature review of PROMETHEE application in energy and environment sectors.

Studies	Application Area
Beynon & Wells, 2008; Kapepula et al., 2007; Linkov et al., 2006; Palma et al., 2007 [66–69]	Environmental Impact Assessment
Cavallaro, 2009; Diakoulaki & Karangelis, 2007; Doukas et al., 2006; 2008, Ghafghazi et al., 2010; Goumas & Lygerou, 2000; Haralambopoulos & Polatidis, 2003; Ren et al., 2009; Pohekar and Ramachandran, 2004; Tsoutsos et al., 2009 [39,61,62,70–76]	Selection & Assessment of Sustainable and Environmental Friendly Technological Options for Energy Generation
Diakoulaki et al., 2007, Vaillancourt & Waaub, 2004 [60,77]	Monitoring GHG Reduction Potential in a Country Level
Geldermann & Rentz, 2005, Mergias et al., 2007	Life Cycle Analysis
Queiruga et al., 2008, Vego et al., 2008 [55,78–80]	Waste Management
Hyde et al. (2003); Madlener and Stagl (2005) [81,82]	Ranking renewable energy technologies and scenarios

2.3.3. MCDM and Fuzzy Set Theory

The questions arising from the aforementioned criteria and which decision-makers are called upon to answer lead to qualitative input data that cannot be determined with a reasonable degree of accuracy. Therefore, fuzzy numbers appear as a more appropriate choice compared to crisp ones, since they can depict data from a more realistic approach [83–86].

The idea of incorporating fuzzy logic into MCDM methods has long being studied in the literature. Especially, in the case of outranking methods, which rely on pair wise comparisons and exploit the notion of preference and indifference, fuzzy logic is interweaved in the methods. As Chen et al. (2010) [87] put it, most outranking methods are based on a fuzzy notion since the comparisons do not hold true with the two-value logic (true/false).

The framework of fuzzy sets offers a simple way of handling problems in which the source of imprecision is the absence of sharply defined criteria of class membership (vagueness) rather than the presence of random variables [88]. In this respect, fuzzy set theory permits the gradual assessment of the membership of elements in a set; this is described with the aid of a membership function valued in the real unit interval [0, 1] [34]. In fuzzy applications, triangular fuzzy numbers (TFN), a special case of a trapezoidal fuzzy number, are widely exploited. According to the definition by Van Laarhoven and Pedrycz (1983) [89], a TFN is characterized by the following properties.

A fuzzy number $\widetilde{A}$ on X is a TFN if its membership function $\mu_{\breve{A}}(\chi)$: X→ [0, 1] equals

$$\mu_{\breve{A}}(\chi) = \begin{cases} \frac{x-l}{m-l}, & | \, l \le x \le m \\ \frac{u-x}{u-m}, & | \, m \le x \le u \\ 0, & elsewhere \end{cases} \quad (1)$$

where l and u are for the lower and upper bounds of fuzzy number $\widetilde{A}$, respectively, and m is median value.

A triangular fuzzy number is denoted as $\widetilde{N}$ = (l, m, u). Four basic arithmetic operations of triangular fuzzy numbers are listed below, as defined by Kaufmann and Gupta (1991) [90]:

Let $\widetilde{N}_1 = (l_1, m_1, u_1)$ και $\widetilde{N}_2 = (l_2, m_2, u_2)$.

i. Addition (+):

$$\widetilde{N}_1(+)\widetilde{N}_2 = (l_1, m_1, u_1)(+)(l_2, m_2, u_2) = (l_1 + l_2, m_1 + m_2, u_1 + u_2))$$

ii. Subtraction (-):

$$\widetilde{N}_1(-)\widetilde{N}_2 = (l_1, m_1, u_1)(-)(l_2, m_2, u_2) = (l_1 - l_2, m_1 - m_2, u_1 - u_2))$$

iii. Multiplication (×):

$$\widetilde{N}_1(\times)\widetilde{N}_2 = (l_1, m_1, u_1)(\times)(l_2, m_2, u_2) = (l_1 \times l_2, m_1 \times m_2, u_1 \times u_2))$$

iv. Division (/):

$$\widetilde{N}_1(/)\widetilde{N}_2 = (l_1, m_1, u_1)(/)(l_2, m_2, u_2) = (l_1/l_2, m_1/m_2, u_1/u_2))$$

Notes:

- It is worth noting that $\widetilde{N}$ (–) $\widetilde{N}$ ≠ 0, $\widetilde{N}$ (/) $\widetilde{N}$ ≠ 1, where 0,1 depict fuzzy numbers (0, 0, 0) and (1, 1, 1), respectively. Therefore, solution $\widetilde{N}$ of the fuzzy equation $\widetilde{N}_2$ = $\widetilde{N}$ (–) $\widetilde{N}_1$ is not, contrary to what is expected, equal to $\widetilde{N}$ = $\widetilde{N}_1$ (+) $\widetilde{N}_2$ [91].
- Notably, the computational results of multiplication (iii) and division (iv) are not TFNs; however, these computational results can be approximated by TFNs. This study adopts a triangular fuzzy number, which is the most common membership function shape. [92].

Additionally, Geldermann et al. (2000) [41] defines the Function Implementation (f) as follows:

v. Function Implementation (f):

$$f\left(\widetilde{N}\right) = f((l_1, m_1, u_1)) = (f\,(l_1), f\,(m_1), f\,(u_1))$$

2.3.4. Literature Review on MCDM Methods and Fuzzy Logic

The information needed to assess the different decarbonisation scenarios especially in the context of energy transition is often unclear, uncertain and difficult to express with quantitative indicators [64]. As Phillis & Andriantiatsaholiniaina (2001) [93] have highlighted, sustainability is an inherently vague concept with parameters that are difficult to quantify.

Many methods of MCDM in fuzzy environment have been developed by Ölçer & Odabaşi (2005), Wang & Lin (2003) and Xu & Chen (2007) [94–96], and many applications benefited from these methods, such the applications of Chen & Tzeng (2011), Chen & Lee (2010); Chen et al. (2008); Chiou et al. (2005), Ding et al. (2005), Wang et al. (2008) [97–102].

Fuzzy AHP

Fuzzy analytical hierarchy process (AHP) has been applied in the energy sector in several studies. Heo et al. (2010) [103] utilized Fuzzy AHP to analyse the assessment factors for renewable energy dissemination program evaluation. Kahraman et al. (2010) [104] applied a comparative analysis for multi-attribute selection among renewable energy alternatives using fuzzy axiomatic design and Fuzzy AHP, while Kaya & Kahraman (2010) [105] used a Vlsekriterijumska Optimizacija I KOmpromisno Resenje (VIKOR) - AHP methodology under fuzziness to the selection of the best energy policy and production site. Luthra et al. (2015) [106] applied Fuzzy AHP for prioritizing of indicators to develop an integrated sustainability assessment framework for energy systems. Based on the results obtained, the 'Environmental' indicator dimension has been reported as the most important dimension for assessing the sustainability in energy planning and management. Fuzzy AHP has been also employed for the assessment of the effectiveness of national R&D actions relevant to renewable energy technologies [107,108], for the choice of goods suppliers [109–112], for the assessment of companies responsible for the collection and transport of hazardous waste [113], for the evaluation of hydrogen production technologies [114], for evaluating the complexity of project management [115]. Sagbas & Mazmanoglu (2014) [116] aimed to determine the weights of criteria for assessment of wind energy production alternatives located in Marmara region of Turkey. For this purpose, they developed a decision model based on the fuzzy AHP method. However, despite its wide and successful applications, in the extent analysis of fuzzy AHP, the priority weights of criterion or alternative can be equal to zero. In this situation, we do not take this criterion or alternative into consideration. This is one of the disadvantages of this method [117].

Fuzzy TOPSIS

The Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method, similar to TOPSIS, also finds application in energy and environmental management and energy planning problems [118]. It has been used to evaluate the viability of renewable energy projects [119–122], to select the appropriate landfill site and method for managing municipal solid waste [123], for the selection of a suitable location for the installation of a power plant [124], for the selection of the most suitable alternative fuel in the transport sector [125], for the environmental assessment of energy suppliers [126], to choose the optimal supplier of goods [127]. Papapostolou et al. (2017) [24] presented a new extension of fuzzy TOPSIS method for prioritization of alternative energy policy scenarios to realize targets of renewable energy in 2030. In addition, the method can also be used on personnel selection problems [128]. Finally, systems based on fuzzy TOPSIS have also been applied for industrial control [129].

Fuzzy SAW

Simple additive weighting (SAW) has had applications in water management, business, and financial management. It is extremely simple to use, but users have applied it in limited applications [56]. The basic concept of SAW method is to find a weighted sum of rating the performance of each alternative on all attributes. A wide variety of Fuzzy SAW applications of solving real-world problems have been reported in the literature. Sagar et al. (2013) [130] present an approach of selection an appropriate maintenance strategy of material-handling equipment in the Punj Lloyd plant Gwalior (India) using Fuzzy SAW method. Rajaie et al. (2010) [131] dealt with the problem of choosing an appropriate contractor for a construction problem, which is a major concern in developing countries by developing a computation method based on Fuzzy SAW for the selecting the right contractor among those who participated in the tender process. Deni et al. (2013) [132] used the method with the aim to help and provide the best decision in the selection of high achieving students in the faculty level. To the best of our knowledge, Fuzzy SAW has a few publications in energy sector, while none of the have been applied in strategic energy planning.

Fuzzy PROMETHEE

The implementation of the PROMETHEE method with linguistic assessments instead of crisp values constitutes the fuzzy PROMETHEE method. This alteration of the original method has been successfully applied to many decision-making problems for ranking and selection among alternatives and fuzzy PROMETHEE has also been applied to studies in the field of energy policy, as it was shown in the introductory section.

In 2000, Goumas and Lygerou [39] proposes an extension of the PROMETHEE method for decision-making in fuzzy environment. In particular, the PROMETHEE II method has been extended to handle data in the form of fuzzy numbers [88]. Both methods, PROMETHEE II and Fuzzy-PROMETHEE, were then applied to the problem of ranking alternative scenarios for the exploitation of a geothermal field of low temperature fluids. Fuzzy-PROMETHEE resulted in a more realistic ranking where the imprecision of the data is taken into consideration. Cavallaro & Ciraolo (2013) [133] used fuzzy PROMETHEE method to make a comparison among a group of solar energy technologies. Chen & Pan (2015) [134] assessed low-carbon building measures. Five criteria and nine alternatives were identified within the context of high-rise commercial buildings in Hong Kong, which are centralized on technical, economic and environmental aspects of building performance. Geldermann et al. (2000) [41] proposed fuzzy PROMETHEE with trapezoidal fuzzy interval numbers and presented an application for the environmental assessment of iron and steel industries. Geldermann and Rentz (2001) [135] also presented fuzzy PROMETHEE for environmental assessment and developed a graphical sensitivity analysis.

In conclusion, with respect to the literature reviews mentioned above, to the best of our knowledge, this is the first fuzzy-PROMETHEE-based MCDM technique for group decision-making developed for ranking transformation pathways for achieving a sustainable European energy future. In doing so, the attempt is to extend the application domains of the fuzzy PROMETHEE method.

2.3.5. Implementation Steps of Fuzzy PROMETHEE

In the proposed methodological framework, the PROMETHEE method, introduced by Brans (1982) [50], is combined with fuzzy logic, developed by Zadeh (1965) [88], in order to exploit a method capable of tackling the transformation pathways problem. Additionally, group decision-making is embedded to depict the pluralism stemming from different stakeholders based on the Tavakkoli-Moghaddam et al. (2015) [136]. The steps of the extension of the fuzzy PROMETHEE method for group decision-making are explained in the following paragraphs [102].

Step 1: Determine alternatives (m), evaluation criteria (k) and group of decision-makers (n).

Step 2: Define linguistic variables and their corresponding triangular fuzzy numbers, based on which the evaluation of the criteria's importance and the ratings of the alternatives will take place.

In the current methodological approach, a five-scale linguistic variable fuzzy number was used, as in the research of Chen and Hwang (1992) [137]. Table 2 indicates the linguistic scales and corresponding triangular fuzzy numbers for weight of criteria and rating of alternatives, respectively. Figure 4 shows the membership function of triangular fuzzy numbers.

Table 2. Linguistic variables and fuzzy numbers.

Weights of Criteria	Fuzzy Number	Ratings of Alternatives
Very Low (VL)	(0.00, 0.00, 0.25)	Worst (W)
Low (L)	(0.00, 0.25, 0.50)	Poor (P)
Medium (M)	(0.25, 0.50, 0.75)	Fair (F)
High (H)	(0.50, 0.75, 1.00)	Good (G)
Very High (VH)	(0.75, 1.00, 1.00)	Best (B)

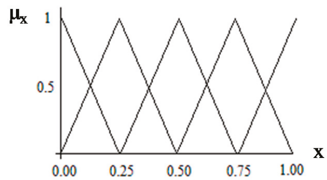

Figure 4. Membership function μ_x of triangular fuzzy numbers.

Step 3: Aggregate decision-maker evaluations. A decision is derived by aggregating the fuzzy weights of criteria and fuzzy rating of alternatives from n decision-makers. In addition, the preferences and opinions of n decision-makers with respect to j criterion (C_j) for the importance weight of each criterion and with respect to i alternative (A_i) for the rating of each alternative to each criterion can be calculated using the Equations (2) and (3).

$$\widetilde{w_j} = \frac{1}{n}\left[\sum_{e=1}^{n} \widetilde{w_j^e}\right] = \frac{1}{n}\left[\widetilde{w_j^1}(+)\,\widetilde{w_j^2}(+)\cdots(+)\widetilde{w_j^n}\right] \tag{2}$$

$$\widetilde{x_{ij}} = \frac{1}{n}\left[\sum_{e=1}^{n} \widetilde{x_{ij}^e}\right] = \frac{1}{n}\left[\widetilde{x_{ij}^1}(+)\,\widetilde{x_{ij}^2}(+)\cdots(+)\widetilde{x_{ij}^n}\right] \tag{3}$$

In the context of this study, it is also assumed that the opinions of the decision-makers are not equally important. In such case, the importance of decision-maker's i opinion is given by variable r_i and table R, as shown in equation (4), includes the importance weights of all decision-makers.

$$R = \begin{bmatrix} r_1 & r_2 & \ldots & r_n \end{bmatrix} \tag{4}$$

Therefore, Equations (2) and (3) are altered as follows:

$$\widetilde{w_j} = \left[\sum_{e=1}^{n} r_e\widetilde{w_j^e}\right] = \frac{1}{n}\left[r_1\widetilde{w_j^1}(+)r_2\widetilde{w_j^2}(+)\cdots(+)r_n\widetilde{w_j^n}\right] \tag{5}$$

$$\widetilde{x_{ij}} = \left[\sum_{e=1}^{n} r_e\widetilde{x_{ij}^e}\right] = \frac{1}{n}\left[r_1\widetilde{x_{ij}^1}(+)r_2\widetilde{x_{ij}^2}(+)\cdots(+)r_n\widetilde{x_{ij}^n}\right] \tag{6}$$

Step 4: Construct a fuzzy decision matrix and compute the aggregated fuzzy weight of criterion [37,92,136].

$$\widetilde{D} = \left[\widetilde{x_{ij}}\right]_{m\times k} = \begin{bmatrix} \widetilde{x}_{11} & \widetilde{x}_{12} & \ldots & \widetilde{x}_{1k} \\ \widetilde{x}_{21} & \widetilde{x}_{22} & \ldots & \widetilde{x}_{2k} \\ \vdots & \vdots & & \vdots \\ \widetilde{x}_{m1} & \widetilde{x}_{m2} & \ldots & \widetilde{x}_{mk} \end{bmatrix} \tag{7}$$

$$\widetilde{W} = \begin{bmatrix} \widetilde{w_1} & \widetilde{w_2} & \ldots & \widetilde{w_k} \end{bmatrix} \tag{8}$$

where $\widetilde{x_{ij}}$ is the rating of alternative A_i with respect to criterion C_j, and $\widetilde{w_j}$ is the importance weight of jth criterion.

Step 5: Choose the Type of the preference function P(d) and determine the corresponding thresholds. The use of Type V (Linear preference function with indifference area) is considered to be more suitable (Figure 5) [41]. The philosophy behind this selection is that fuzzy implementation aims at quantitating the qualitative criteria (as well as our original data, i.e., the evaluations of the alternatives). According to the literature [41], Type V is more appropriate for quantitative criteria. One reason for this is that the quantitative criteria receive constant values (unlike the qualitative that receive distinct e.g., bad, medium, good), so the preference function is preferable to be linear. For this reason, the remaining types of preference function (I, II, III, IV) are not selected in this study, as they cannot support the concept of linear preference, but instead define levels of preference, which is closer to the philosophy of the qualitative scale.

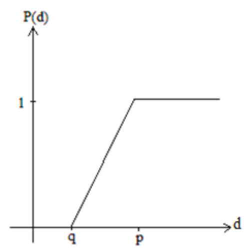

Figure 5. Type V preference function.

Initially, thresholds are defined as follows: indifference threshold q for criterion j is set to the smallest difference between two alternative ratings with respect to criterion j, and preference threshold p for criterion j is set to the maximum difference between two alternative ratings with respect to criterion j.

Step 6: Generate the fuzzy multi-criteria preference index $\widetilde{\pi}$ for each pair of alternatives A_i, A_j according to Equation (9) [41,92].

$$\widetilde{\pi}\left(A_i, A_j\right) = \frac{\sum_{t=1}^{k} \widetilde{w_t}\ (x)\ p_t(x_{it}(-)x_{jt})}{\sum_{t=1}^{k} \widetilde{w_t}} \tag{9}$$

where $p_t\left(x_{it}(-)x_{jt}\right)$ is the preference degree resulting from the comparison between alternatives A_i, A_j with respect to criterion t, which is calculated as the value of the preference function $p_t()$ based on the difference–subtraction operation (ii)–between the two alternative's ratings based on the Function Application operation (v). Finally, the total sum is calculated according to Addition operation (i).

Step 7: Calculate fuzzy Leaving Flow $\widetilde{\Phi^+}(A_i)$, as a measure of the superiority of the alternative A_i (10) and fuzzy Entering Flow $\widetilde{\Phi^-}(A_i)$, as a measure of the inferiority of alternative A_i (11). In the particular study we obtain a complete ranking of the four alternative transformation pathways. To this end, the difference of the aforementioned quantities produces the fuzzy Net Flow based on the PROMETHEE II method (12) [41,92].

$$\widetilde{\Phi^+}(A_i) = \frac{1}{m-1} \cdot \sum_{j=1}^{m} \widetilde{\pi}\left(A_i, A_j\right) \tag{10}$$

$$\widetilde{\Phi^-}(A_i) = \frac{1}{m-1} \cdot \sum_{j=1}^{m} \widetilde{\pi}\left(A_j, A_i\right) \tag{11}$$

$$\widetilde{\Phi}(A_i) = \widetilde{\Phi^+}(A_i)(-)\widetilde{\Phi^-}(A_i) \tag{12}$$

Step 8: The final total ranking is achieved after defuzzification of fuzzy Net Flow. There are many models that could be exploited at the defuzzification process but none of them could be considered as optimum under all circumstances. Based on the philosophy of outranking methods, and especially of PROMETHEE, the approach applied ought to be as easy as possible to be used at the decision-making process [41]. Consequently, the proposed assessment is based on the approach Centre of Area (COA) [138] according to equation (13), which is the most widely used option [139]. For the sake of brevity, we define $\widetilde{\Phi}(A_i) = x_i$.

$$x_i^{defuzz} = \frac{\int x_i \cdot \mu(x_i) dx_i}{\int \mu(x_i) dx_i} \tag{13}$$

where $\mu(x_i)$ is the membership function of fuzzy number x_i.

The final ranking of the problem's alternatives is obtained directly from sorting all the defuzzified x_i.

In order to implement and calculate the methodological steps suggested above the need for a new program that implements fuzzy PROMETHEE has occurred. Therefore, the algorithm explained in this section was implemented in Python 3.6 and the program was run in the Microsoft Azure Notebooks environment [140]. More precisely, the NumPy library was used for the numerical calculations and the csv library for the processing of spreadsheets that contained the input data, namely:

- Criteria Weights;
- Rating of the alternatives by the DMs;
- Parameters/Configurations for each scenario, which are the DMs' contributions and the threshold values.

3. Results

Following the presented steps, this research used a total of three decision-makers (DMs) Dr, r = {1, 2, 3}, four different criteria C_j, j = {1, 2, 3, 4}, and four alternative policy scenarios A_i, i = {1, 2, 3, 4}.

The next step concerns data collection so as to represent decision-makers' value system through definition of criteria weights and alternative ratings. Due to the diversity of stakeholders, three main decision-maker profiles were defined that represent: a policymaker(DM_1), an entrepreneur–representative of the energy industry (DM_2), and a researcher–representative of the academia (DM_3).

Their views regarding the importance of each criterion and the evaluation of the alternatives are shown in Tables 3 and 4. More particularly, Table 3 includes each DM's opinion on the importance of each criterion with regards to the transformation pathways assessment. The evaluation of the importance of each criterion are in the form of linguistic variables [Very Low (VL)-Low (L)-Medium (M)-High (H)-Very High (VH)] (see Table 2).

Respectively, Table 4 presents the performance of each of the four alternative pathways in each of the four criteria, according to the DMs' opinion [Worst (W)-Poor (P)-Fair (F)-Good (G)-Best (B)] (see Table 2).

Table 3. Criteria weights.

Decision-Makers	Weights			
	C_1	C_2	C_3	C_4
D_1	VH	M	VH	M
D_2	H	VH	M	M
D_3	M	M	VH	VH

At this point, it is important to underline that in an attempt to explore the stability of the produced results, sensitivity analysis was conducted. Sensitivity analysis helps to understand how the model variables react to input changes, and whether they are related to the data used to adapt the structure of the model, or to independent variables of the model [141]. This mechanism is used to increase the reliability and improve the outcomes of the model [142]. More precisely, multiple iterations (scenarios) of the methodology were carried out, that differentiate themselves in terms of DMs' importance and values of thresholds, as explained below.

Table 4. Rating of the alternatives by the DMs.

DM	Criteria	Alternatives			
		A_1	A_2	A_3	A_4
D_1	C_1	F	B	G	B
	C_2	P	F	G	B
	C_3	P	G	F	F
	C_4	G	G	P	F
D_2	C_1	F	B	G	G
	C_2	P	G	B	B
	C_3	F	G	F	G
	C_4	G	F	P	G
D_3	C_1	G	B	G	B
	C_2	P	G	G	B
	C_3	P	G	F	P
	C_4	B	F	P	F

Consequently, concerning the aggregation step (see Section 2.3.5, Step 3) of the above-mentioned views, four different scenarios were developed in an attempt to explore possible changes in the final ranking. These scenarios vary from each other in terms of importance that is attributed to each DM and therefore they produce different evaluation tables on step 4:

- 1st Scenario (reference): DMs are considered to be equal (33.33%) and their opinions contribute to the same extent in the final ranking.
- 2nd–4th Scenarios: In these scenarios, greater emphasis is placed on the opinion of one DM each time (60%), while the views of the other two contribute secondarily to the final ranking (20% each).

For each of the four scenarios and based on the preference function selected in step 5, the values of the preference threshold p and indifference threshold q were initially selected so as not to affect the results, as explained in step 5. Because of this, the first scenarios are labelled as "no threshold" when commenting on the results.

Based on these four scenarios, four additional repeats of the method were produced in order to assess the sensitivity of the final ranking, by progressively decreasing the value of preference threshold p and increasing the value of indifference threshold q, as suggested by the literature (Table 5). It should be highlighted that as part of the sensitivity analysis of the results, other iterations of the method were carried out with intermediate threshold values. However, these were not considered necessary to be presented, as the rankings for the different threshold values in Table 5, are sufficient to confirm that the results are sufficiently robust.

During the final steps, the fuzzy PROMETHEE algorithm written in Python generates the fuzzy multi-criteria preference index $\widetilde{\pi}$ (step 6), the flows (step 7) and at last implements the defuzzification process (step 8) that produces the overall ranking of the transition pathways.

More precisely, leaving, entering and net flows of each alternative for all eight scenarios are presented on Tables 6 and 7. As mentioned in step 7, the fuzzy Leaving Flow $\widetilde{\Phi^+}(A_i)$ measures the sum of preference that alternative A_i is better from another options and fuzzy Entering Flow $\widetilde{\Phi^-}(A_i)$ demonstrates the sum of preference that other options are superior to alternative A_i, while the final ranking of the four alternative transformation pathways is obtained from the difference of the aforementioned quantities, which produces the fuzzy Net Flow based on PROMETHEE II method.

Table 5. Values attributed to thresholds.

Iterations	**Criteria**	**Thresholds**	
		p	**q**
No thresholds	C_1	1.00	0.25
	C_2	1.00	0.00
	C_3	1.00	0.00
	C_4	1.00	0.00
With thresholds	C_1	0.65	0.60
	C_2	0.65	0.35
	C_3	0.65	0.35
	C_4	0.65	0.35

Repetitions for the first, second and fourth scenarios produced similar results and a graph is illustrated to depict schematically the corresponding flows, indicatively for the first scenario (Figure 6). Respectively, for repetitions of the third scenario (where the opinion of the representative of the energy industry has priority) the flows are presented in Figure 7. The same results are obtained in the case of "with threshold".

Table 6. Alternative flows for all scenarios (no thresholds).

Scenario 1 equal DMs–R = [0.33, 0.33, 0.33]				
Flows	Alternatives			
	A_1	A_2	A_3	A_4
Leaving	1.14	2.42	1.61	2.22
Entering	3.11	1.12	1.94	1.22
Net	−1.97	1.3	−0.33	1
Scenario 2 priority on D_1–R = [0.6, 0.2, 0.2]				
Flows	Alternatives			
	A_1	A_2	A_3	A_4
Leaving	1.04	2.49	1.56	2.22
Entering	3.14	1.04	1.94	1.2
Net	−2.1	1.46	−0.38	1.02
Scenario 3 priority on D_2–R = [0.2, 0.6, 0.2]				
Flows	Alternatives			
	A_1	A_2	A_3	A_4
Leaving	1.02	2.35	1.67	2.34
Entering	3.29	1.13	1.86	1.1
Net	−2.26	1.22	−0.19	1.23
Scenario 4 priority on D_3–R = [0.2, 0.2, 0.6]				
Flows	Alternatives			
	A_1	A_2	A_3	A_4
Leaving	1.38	2.42	1.64	2.11
Entering	2.9	1.19	2.05	1.41
Net	−1.52	1.23	−0.41	0.7

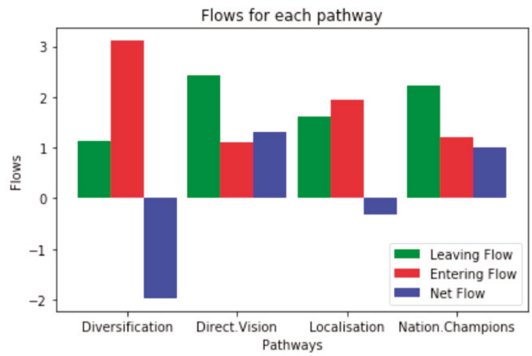

Figure 6. Flows representation for alternative pathways in scenario 1 (no thresholds).

Table 7. Alternative flows for all scenarios (with thresholds).

Scenario 1 equal DMs–R = [0.33, 0.33, 0.33]				
Flows	Alternatives			
	A_1	A_2	A_3	A_4
Leaving	1.01	2.13	1.49	1.99
Entering	3.2	0.94	1.53	0.95
Net	−2.19	1.19	−0.03	1.04
Scenario 2 priority on D_1–R = [0.6, 0.2, 0.2]				
Flows	Alternatives			
	A_1	A_2	A_3	A_4
Leaving	0.89	2.25	1.46	1.95
Entering	3.18	0.82	1.53	1.01
Net	−2.29	1.43	−0.07	0.94
Scenario 3 priority on D_2–R = [0.2, 0.6, 0.2]				
Flows	Alternatives			
	A_1	A_2	A_3	A_4
Leaving	0.93	2.07	1.46	2.01
Entering	3.39	0.86	1.45	0.77
Net	−2.46	1.22	0.01	1.23
Scenario 4 priority on D_3–R = [0.2, 0.2, 0.6]				
Flows	Alternatives			
	A_1	A_2	A_3	A_4
Leaving	1.21	2.15	1.53	1.94
Entering	3.08	1	1.63	1.12
Net	22121.87	1.15	−0.09	0.82

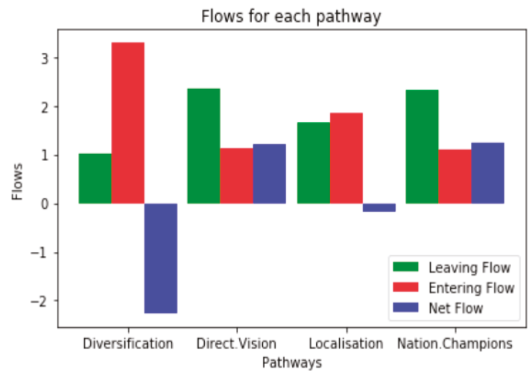

Figure 7. Flows representation for alternative pathways in scenario 3 (no thresholds).

The resulting ranking is $A_2 > A_4 > A_3 > A_1$ for all scenarios, with the only exception taking place in the 3rd scenario where A_2 is marginally supplanted by A_4, as presented in Table 8.

Table 8. Summary of rankings for all scenarios.

Alternatives	**Scenarios**							
	No Threshold				**With Threshold**			
	1st	**2nd**	**3rd**	**4th**	**1st**	**2nd**	**3rd**	**4th**
A_1	4	4	4	4	4	4	4	4
A_2	1	1	2	1	1	1	2	1
A_3	3	3	3	3	3	3	3	3
A_4	2	2	1	2	2	2	1	2

4. Discussion

First of all, the comparative study of the above results demonstrates a high rate of agreement between the rankings of different scenarios, confirming the practical interest and usefulness of the proposed methodology as a tool to support the decision-making process of assessing the energy transformation pathways. Also, according to a relevant study by Cavallaro & Ciraolo (2013) [133] that compared a set of solar energy technologies using fuzzy PROMETHEE, the method seems to be able to provide a technical–scientific decision-making tool that can be efficiently integrated with linguistic information giving valuable assistance to decision and policymakers in the field of energy.

In the majority of all scenarios, "Directed Vision" stands out as the most preferred pathway, followed by "National Champions". These two pathways show positive net flow values, which is translated as follows: The measure of the superiority of these pathways (Leaving flow) is greater than the absolute value of the measure of their weakness (Entering flow). However, this does not hold true for the other two alternatives, namely "Localisation" and "Diversification", which have negative net flows.

The only cases where "National Champions" supplants "Directed Vision" are the two iterations of the third scenario. Although this supremacy is only marginal, since net flows of the two pathways differ only to the second decimal, it is worth exploring, why this has occurred. More specifically, the differentiation element between scenarios is found in the greater weight that is attributed to a different decision-maker each time. In turn, each decision-maker differs from the others in terms of alternative ratings and criteria weights.

In this case, the third scenario concerns the second decision-maker (DM_2) and by studying Tables 2 and 3, the following are observed: For none of the criteria, DM_2 underestimates "Directed Vision" compared to the other decision-makers, whereas DM_2 gives a higher ranking to "National

Champions" only in regard to the criterion C_4. However, the fourth criterion does not have the greatest importance for DM_2 and therefore this differentiation is not the main reason why changes are observed in final rankings. Instead, the predominant cause of the small variations in rankings lies in the attribution of weights, since DM_2 gives greater importance to C_2, in comparison with the other decision-makers, a criterion to which "National Champions" performs better than the "Directed Vision". In other words, "National Champions" has a noticeable sensitivity to C_2, as a change in its weight is likely to cause deviations of the results.

This assessment is dedicated to introducing and providing a direction towards a most preferable pathway concept, as well as an overall approach that should be taken into account by a future model-based analysis of the necessary transformation of our energy sector to cope with the requirements of a decarbonisation.

Policymakers and all relevant stakeholders could be facilitated in the drawing the energy transition priorities take into account the results of the assessment. "Directed vision" pathway lays emphasis on cooperation between countries on technology advancement, diversification of flexibility options for RES integration (but with prioritising of centralised solutions), a strong expansion in grid capacity and a balanced mix in energy supply, including new nuclear, CCS, and RES (with focus on centralised options). Remarkably, it is noted here the strongest EU energy systems integration (prioritizing interconnections). Towards this direction, the cross-border cooperation seems to play a crucial role in achieving the energy transition. Finally, this analysis may serve as a guidance to policymakers towards their efforts to plan climate and energy strategies by using the information of this approach and prioritizing uncertainties from an environmental and energy perspective.

5. Conclusions

This paper presents a multi-criteria approach based on an extended fuzzy PROMETHEE for group decision-making. The approach is used to evaluate alternative transformation pathways for achieving a free-carbon and sustainable energy future in the EU.

The recognition of the multidimensional nature inherent in the alternative choices regarding the European energy future and the treatment of the problem as a multifactorial one abolishes the obsolete one-dimensional approach that seeks to find a transformation pathway that will be optimal in light of a specific objective, such as the participation of RES in the energy mix or the transition cost.

The proposed approach and the developed methodological framework could be a useful tool for decision-makers and stakeholders in the energy market. First, by choosing a representative set of criteria, the realistic modelling of the problem under study is achieved, since the fundamental and often conflicting aspects that determine whether strategies followed will lead to a sustainable energy system, are clearly outlined. Secondly, with the definition of thresholds, criteria weights and alternatives ratings, an accurate mathematical representation of the decision-makers' preference system is achieved, thus integrating them into the process of the pathways evaluation.

Of course, the impact of the linguistic variables is remarkable, too. The process becomes friendlier to the decision-makers and at the same time the uncertainty in their words is taken into consideration and it is encoded in the input data thanks to the use of fuzzy numbers. Moreover, the proposed methodology contributes to achieving consensus as it enables the views of different decision-makers to be aggregated, thus promoting group decision-making, which is inherent in the application problem, given that numerous and heterogeneous stakeholders are involved and that they have different views and intentions.

Taking into account the overall results of this methodological process, it appears that the decision-makers unanimously believe that "Directed Vision" and "National Champions" have the best prospects of thriving and bearing positive consequences concerning EU's attempt to transform the energy sector and achieve its decarbonisation. According to the majority of scenarios, the more progressive "Directed Vision" outperforms the more conservative "National Champions". However, the generalization of the aforementioned finding is considered precarious and it is more realistic to suggest that there are more to be gained if policymakers and those involved in the energy market formulate proposals and strategies that divert the European energy future from "Localisation" and "Diversification" pathways.

To further improve the decision model, it is suggested to assess it under more realistic conditions. Including more experts and policy-makers in the process will result in even more efficient modelling of the problem and hence more realistic results will be extracted that correspond to the specific value system of each decision-maker. The reason for this is that decision-makers, not only attribute different weights to the criteria, but they can also suggest new criteria to include, so that their personal opinions are reflected. Consequently, an enriched and more complete set of criteria will be formed. More precisely, when assessing the pathways financial and societal impact could be taken into consideration, as well. Additionally, further evaluation of the same alternatives could be pursued, too. In other words, it is proposed that the pathways be evaluated and compared based on their performance in key technological aspects (e.g., case studies on renewable energy sources, smart grids, energy efficiency, sustainable transportation, carbon capture and storage technologies and nuclear safety). The development of this alternative model is meant to shed light on the more complex and specialized technological factors that play a major role in the energy systems.

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A Hybrid Multi-Criteria Methodology for Solving the Sustainable Dispatch Problem

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Abstract: Wind energy is becoming an increasingly substantial component of many nations' energy portfolios. The intermittent nature of wind energy is traded off in a multi-objective sense against its environmental benefits when compared to conventional thermal energy sources. This gives rise to the multi-criteria sustainable dispatch problem considered in this paper. A relevant multi-objective model is formulated considering both environmental and economic criteria as well as ensuring adequate production levels. The techniques of weighted goal programming (WGP) and the progressive bounded constraint method (PBC) are combined in a novel manner in order to overcome computational challenges associated with the sinusoidal nature of the model. This allows the generation of a representative set of Pareto efficient solutions. The proposed methodology is demonstrated on a test set of relevant examples, and conclusions are drawn from both methodological and application perspectives. The results provide a quantification of the economic and environmental benefits of added wind power to a solely thermal system. However, a trade-off between the levels of economic versus environmental benefits gained is also demonstrated.

Keywords: wind energy; multi-objective optimization; weighted goal programming; progressive bounded constraint

1. Introduction

The wind power industry has undergone a period of substantial growth in recent decades. Initially, this involved wind farms being built onshore, but has more recently also involved the planning and operation of offshore wind farms as well. Attributes in the growth trend include larger turbines with a greater per turbine electricity production capacity and larger farms in terms of geographical area and number of turbines, particularly in the offshore case. In terms of geographic zones, wind energy can be seen as an increasingly global phenomenon, with Asian, North American, European, and South American countries represented in the top ten producers by installed capacity, and a global installed capacity of 651 GW by the end of 2019. With respect to this global growth, wind power can be seen as following a similar trend to that of other renewable energy sources, with particular growth seen in the solar [1] and biofuel [2] sectors. Other sources, such as wave and tidal [3], are at a more emergent phase of their technological lifecycle, but offer good future potential. Comparative analyses of renewable energy sources can be found in Lee and Chang [4] and Salim and Alsyouf [5].

The above growth highlights the need for the continued consideration of multiple sustainability dimensions in the global wind industry. There is a growing body of literature on the topic. The trade-offs between the key economic, environmental, social, and technical sustainability criteria for a range of decision-making situations can be analyzed using multiple-criteria decision-making (MCDM) methods. This can apply to a range of strategic and operational decision problems arising throughout the lifecycle of a wind farm. Recent works in this regard include that of Rehman et al. [6], who consider the location of onshore wind farms from a discrete set of alternatives. Seventeen underlying criteria across economic, environmental, social, and technical sustainability dimensions are considered, and the authors apply the Promethee MCDM methodology to investigate multiple criteria trade-offs and, hence, suggest optimal locations. Jones and Wall [7] also consider wind farm location with a discrete set of alternatives, but in the offshore context. Economic (life cycle costs), environmental (impact on locality), social (effects on other maritime users), and technical (power generated by season) sustainability goals are considered. The MCDM technique of goal programming is used to suggest optimal location strategies under different values of decision-maker importance assigned to the criteria. Konneh et al. [8] consider the place of wind energy in an enhanced sustainable energy portfolio for Sierra Leone. Economic (life cycle costs), technical (reliability, deficiency probability) and environmental (CO_2 emissions) criteria are considered. A multiple-objective particle swarm method is used to generate Pareto sets that illustrate the trade-offs between criteria. Akbari et al. [9] use the technique of Data Envelopment Analysis (DEA) to assess the efficiency of offshore wind farms in Northwestern Europe. Considering design aspects, De La Fuente et al. [10] use the Analytical Hierarchy Process to evaluate wind turbine tower designs. Economic (life cycle costs), environmental (material and energy consumption, CO_2 emissions), and social criteria (accident risk, visual perception, and patents generated) are considered.

The above works largely concentrate on strategic aspects of wind farm location and design. The methodology proposed in this paper focuses on the multi-criteria problem of effectively dispatching the electricity produced from wind farms when combined with conventional sources in a power grid network.

Considering dispatch problems specified in the literature, the single-objective economic dispatch problem with the inclusion of wind power aims to minimize the costs of wind power generation, which is related to weather factors, such as wind speed, which is a random variable. Thus, the model is stochastic because of the influence of wind behavior, which presents velocity variation over short time intervals. In models that analyze wind energy production, a Weibull probability distribution function is considered due to its ability to make wind predictions using relatively limited data [11]. The multi-objective sustainable (economic and environmental) dispatch problem for a traditional thermal generation system aims to minimize both the cost of fuels and the emission of pollutants that occur through the burning of fossil fuels, whilst at the same time meeting the operational constraints of the system. Hetzer, Yu, and Bhattarai [11] propose a combined thermal and wind economic dispatch model with the objective of minimizing the fuel costs of thermal plants and the costs of wind generation. System constraints include the fulfillment of demand and respecting the operating limits of both the thermal and wind generators. The consideration of the joint cost of thermal and wind generation and the focus solely on economic costs enable the authors to solve the model as a single objective problem. An explanation of some distinct cases related to the cost coefficients associated with these integrals, thus presenting the behavior of the wind and thermal generators in relation to their variation, is given in the paper. Güvenç and Kaymaz [12] also propose a thermal and wind economic dispatch model with the aim of minimizing thermal power fuel costs and wind generation costs whilst meeting a demand and considering the insertion of losses in the transmission of the electric power system. The model was solved by a COA (Coyote Optimization Algorithm), which is a recent heuristic algorithm based on population and swarm intelligence, where the main inspiration is coyote behavior. The results were compared with those obtained by GA (Genetic Algorithm) and PSO (Particle Swarm Optimization).

A multi-objective model is proposed in Qu et al. [13], which minimizes the economic and environmental functions of thermal generators. The wind generators are included in the model constraints, where the generation of thermal and wind units must cover the demand and the losses of power transmission, the reserve capacity of the system, and the production limits of thermal generators. The multi-objective evolutionary meta-heuristic NSGA-II (Non-dominated Sorting Genetic Algorithm II) is used, which is based on the concept of dominance and preservation of the solution curve diversity. Additionally used is the SMODE (summation-based multi-objective differential evolution) method, which is a heuristic method for solving multi-objective problems based on differential evolution algorithms.

A further multi-objective model approach is presented by Zhang et al. [14], which includes three objective functions: An economic function presented in Hetzer, Yu, and Bhattarai [11], which adds the cost function of thermal and wind generators, an environmental function, and a loss function in the transmission grid, where the constraints are related to energy balance and safety restrictions. The multi-objective problem is transformed into single-objective sub-problems, which are solved by a new approach of a differential evolution algorithm called GPBNI (generalized piecewise normal boundary intersection). A comparison of the GPBNI results with those of other works found in the literature is given.

Discussions regarding the modeling of trade-offs of environmental and economic sustainability issues in energy production are found in recent articles by Rajagopalan et al. [15], Zhu et al. [16], and Singh and Mishra [17]. According to Zhu et al. [16], wind energy production is more complicated to incorporate in an optimization problem because of its inherent stochasticity derived from wind randomness. One way to address the stochasticity of the problem is to turn it into an equivalent deterministic problem, as found in Yin and Zhao [18], which transforms this problem into a mixed integer programming problem. For multi-objective problems, one of the strategies relating to the inherent structure is to merge two objectives into a single objective function and solve the resulting model using the weighted sum method, as seen in El-Sehiemy, Rizk-Allah, and Attia [19].

Advancing upon the cited works above, this paper proposes a hybrid methodology that includes the sustainable criteria of the economic and environmental dispatch of thermal power and the economic dispatch of a wind farm. This results in a multi-objective model that simultaneously minimizes production costs and the emission of polluting gases. This is achieved whilst meeting a given production demand with the insertion of losses incurred in the transmission of the electricity in the power system and operational constraints of thermal and wind generators. The combination of these problems into a single model is termed the multi-objective wind–thermal economic and environmental dispatch problem (WTEEDP). Most of the works found in the literature that deal with WTEEDP do not use deterministic methods for its resolution and do not address the issue of environmental dispatch in its formulation, which are the objectives of this paper.

A further point of novelty is that the deterministic methodology proposed in this paper for the WTEEDP solution combines two multi-objective problem-solving methods: The progressive bounded constraints (PBC) method developed in Dos Santos et al. [20] and Gonçalves et al. [21], and the goal programming technique detailed in Jones and Tamiz [22]. Interior point methods, detailed, among others, in Mehrotra [23] and Bertsekas et al. [24] and available in Gams software, are used to solve the developed model. In the proposed model, the cost functions of thermal and wind dispatch are combined, as in Hetzer, Yu, and Bhattarai [11] and Güvenç and Kaymaz [12], hence ensuring that this problem has two distinct objectives and enabling the use of the above-mentioned multi-objective methods.

The PBC turns the original problem into a set of single-objective sub-problems, keeping one of the functions as the objective of the problem whilst converting the other objective function into upper and lower bounded constraints. It is hence iteratively used in order to determine an approximation of the Pareto optimal set of the problem. With sufficiently rigorously set target values, the goal programming technique also allows the determination of solutions to the problem that belong to the Pareto optimal set. The weighted goal programming variant is used in this paper, which utilizes a set of weights determined by the levels of importance that the decision-maker gives to the minimization of unwanted deviations from the goal target values. Solving the goal programming model for multiple sets of weights enables the generation of a set of solutions that belong to the Pareto optimal set determined by the PBC method and that give a trade-off between the different underlying objectives. Thus, one technique is corroborated by the other and vice versa. Based on PBC and weighted goal programming, a new composite technique is hence proposed in this work, termed weighted goal programming with progressive bounded constraints (WGPPBC). This is necessary because of the difficulty presented in the resolution of a sine absolute value function that appears in the problem constraints.

This paper aims to show how the inclusion of wind turbines in the power generation system can produce new solutions that are Pareto efficient with respect to environmental impact and the cost of production whilst fulfilling the pre-established demand with consideration of losses. In comparison with a model that just includes thermal sources, this paper attempts to show that inclusion of wind turbines can, in some cases, improve both environmental impact and cost of production, thus improving the sustainability of the system. A further contribution of this work is in solving a multi-objective model that is stochastic in nature due to the use of a random variable describing the wind energy by utilizing a deterministic approach for its resolution, in contrast to the results found in the literature (e.g., Hetzer, Yu, and Bhattarai [11], Qu et al. [13], and Güvenç and Kaymaz [12]).

The main aims of this paper are (i) to quantify the level of environmental and economic benefit achieved by adding wind power units into a conventional thermal power system and (ii) to quantify any trade-offs that occur between environmental and economic gains when adding wind power units into a conventional thermal power system. Both aims (i) and (ii) are in the context of modeling the economic–environmental dispatch problem and link to wider concepts of enhancing the sustainability of power systems. The results should be of interest to planners of new or upgraded power systems, as well as governmental and private decision-makers needing to enhance the sustainability of their power systems.

The remainder of this work is divided and organized as follows: Section 2 presents the WTEEDP formulation, the economic and environmental objectives of thermal power generation, and the economic objective of the wind system, which is based on a Weibull probability distribution. The model has the insertion of valve loading points; hence, the treatment of the resulting modular terms in the economical objective of thermal generation is also addressed. Section 2.4 presents the progressive bounded constraint method (PBC), the weighted goal programming technique (WGP), and the WGPPBC technique used due to the sinusoidal function in the model. Section 3 presents the results obtained in the case for the WTEEDP in different instances of the power generation system. Finally, conclusions are drawn with respect to the proposed methodology and its application in Section 4.

2. The Mathematical Model

As detailed in the previous section, a sustainable dispatch model containing economic and environmental objectives is proposed in this paper. In the literature, the economic objective (Fe) is a quadratic and convex function (without the insertion of a loading valve point), defined as the summation of the cost function related to the fuel costs of each generator (Steinberg and Smith [25]).

The environmental impacts caused by thermal generators were not historically emphasized, as the economic issue was a priority in the production of thermal energy. However, with the increase in the emission of gases into the atmosphere, the need to use generators that caused less environmental damage arose, but their generation costs were higher. The environmental dispatch objective aims to reduce the emission of pollutants, hence considering the environmental conditions and emission reduction for a thermal energy generation system.

A wind farm dispatch model should consider production costs, which are currently low compared to other renewable energy sources. In addition, to be considered are the fulfillment of specific demand and the operational constraints of the wind generators according to their production limitations. The economic objective of wind power generation (Fw) should incorporate the uncertainty of wind speed and, hence, the level of power generation. The cost of wind power production is hence composed of three different cost types: The linear cost (C_w), the penalty cost (C_p), and the reserve cost (C_r).

These are, respectively, the cost associated directly with the amount of energy produced, the cost representing the difference between the available wind energy and the amount used, and the cost representing the uncertainty of the available wind energy generation being less than the planned level. Due to the aforementioned uncertainty in wind energy production, in this work, the penalty cost and reserve functions use a Weibull probability distribution in their formulation. Definitions regarding this function are based on Hetzer, Yu, and Bhattarai [11].

When inserting the losses in the transmission of the electricity of the power system, the Kron formula is used, which represents these losses through the B-coefficient matrix, where the generated power has to be enough to supply the demand as well as the system losses of transmission (Silva [26]).

2.1. Multi-Objective Wind–Thermal Economic and Environmental Dispatch Problem (WTEEDP)

The mathematical model formulated by modeling the above objectives and constraints is termed WTEEDP and is algebraically represented as:

$$Minimize \left\{ \sum_{j=1}^{m} Fe + \sum_{i=1}^{n} Fw \, , \sum_{j=1}^{m} Fa \right\} \tag{1a}$$

$$subject\ to \sum_{i=1}^{n} Pw_i + \sum_{j=1}^{m} Pt_j = D + L \tag{1b}$$

$$0 \leq Pw_i \leq Pw_i^{max} \tag{1c}$$

$$Pt_j^{min} \leq Pt_j \leq Pt_j^{max} \tag{1d}$$

in which:

(1a) is the bi-objective function of the problem.
(1b) is the constraint of meeting the demand of the power generation system.
(1c) is the constraint that imposes the power limitations of the wind power generators.
(1d) is the constraint that imposes the power limitations of the thermal generators.

The sustainability functions of the problem involving Fe, Fa, and Fw, expressed in (1a), are defined as:

Fe: Economic function of thermal plants, defined by:

$$Fe = \sum_{j=1}^{m} a_j P_{t_j}^2 + b_j P_{t_j} + cj + \mid e_j\, sen\, (f_j\, (P_{t_j}^{min} - P_{t_j}), \mid \tag{2}$$

where a_j, b_j, c_j, e_j, and f_j represent the coefficients of the economic function of the generating unit j. The absolute value term represented in (2) is associated with the effect of the valve loading points and transforms the objective function (2) into non-differentiable (at these points) and non-convex modular terms. This non-differentiability will be considered in Section 2.3.

Fa: Environmental function of the thermal plants, defined by:

$$Fa = \sum_{j=1}^{m} A_j P_{t_j}^2 + B_j P_{t_j} + C_j, \tag{3}$$

where A_j, B_j, and C_j are the values of the environmental function coefficients of the j generating unit.

Fw: Economic function of the wind farms, defined by:

$$Fw = C_w + C_p + C_r, \tag{4}$$

where C_w, C_p and C_r are respectively the linear, penalty, and reserve costs defined in Section 2.2, modeled as Weibull functions.

2.2. Economic Function of Wind Farms

The economic dispatch problem related to wind power energy aims to minimize the costs of wind power generation. As previously mentioned, this function will be stochastic due to the uncertain nature of wind speeds. The Weibull probability distribution is the most frequently used for checking wind speed frequency curves because of its simple graphical representation and its probability density function being a variant of Gamma probability distribution (Da Silva, Alves, and Cavalcanti [27], Gabriel Filho et al. [28], Al-Hasan and Nigmatullin [29], and Nascimento et al. [30]).

The resulting Weibull probability density function (pdf) is represented as:

$$fV\,(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} exp\left(-\frac{v}{c}\right)^{k} \qquad 0 < v < \infty, \tag{5}$$

in which:

v: Wind speed.
c: Scale factor of a location (with unit of measure equal to wind speed).
k: Form factor of a location (dimensionless).

The c scale factor presented in (5) is directly related to the average speed and classifies the wind speed at the location where the wind farm is installed. The k form factor refers to the uniform distribution of the wind speed values and is known as the distribution inclination (Rocha et al. [31]).

The use of the function (5) in the wind power energy conversion system is given by the probability distribution function (PDF) in (6):

$$FV\,(v) = \int_{v}^{0} fV\,(\Gamma)\; d\Gamma \;=\; 1 - exp\left(-\left(\frac{v}{c}\right)^{k}\right). \tag{6}$$

Due to the characteristics of wind speed, the distribution of wind farms in the wind energy conversion system (WECS) can be modeled as either a discrete or continuous distribution, with the continuous case utilized in this paper as described below. This is due to a linear transformation of the probability density function (5) to the wind speed (m/s), where an analysis is performed to determine the output power. Equations (7)–(9) show how speed wind variation determines the output power of generated energy.

$$w = 0 \qquad v < v_i \;\; e \;\; v > v_o \tag{7}$$

$$w = w_r \frac{(v - v_i)}{(v_r - v_i)} \qquad v_i \leq v \leq v_r \tag{8}$$

$$w = w_r \qquad v_r \leq v \leq v_o \tag{9}$$

Equations (7)–(9) assume that some wind speed limiters are required for the wind power generator to produce energy. Initially, we do not have an output power of energy generated, because in order for the turbines to operate, it is necessary that the wind reaches an initial speed (v_i). When the wind speed is between the cut-in wind speed (v_i) and the rated wind speed (v_r), this relationship is linear, where the generated power gradually increases until it reaches its rated power (w_r). The v_r speed is determined by the nominal speed because of the output power (w_r) that represents the wind generator capacity limit. The rated power remains constant between the rated wind speed (v_r) until it reaches the cut-off speed (v_o), which serves to stop the wind generator energy production in order to avoid structural damage to turbines. The output power (w) for the WECS is, therefore, a mixed random variable, as it is continuous in the wind speed range for $v_i \leq v \leq v_r$ and a discrete variable in the wind speed ranges for $v < v_i$, $v > v_o$, and $v_r \leq v \leq v_o$. The representation of this function for the discrete case, not explored in this paper, can be seen in Hetzer, Yu, and Bhattarai [11].

To use the function (6) to determine the wind speed distribution, a transformation of this distribution is required to make the WECS compatible, i.e., the function is transformed to no longer depend on the incidence of wind speed—it considers only its expression in relation to the power of wind generators. The Weibull probability distribution function for the WECS is hence transformed in order to be represented as (10):

$$fW(w) = \frac{k\,l\,v_i}{c}\left(\frac{(1+\rho\,l)\,v_i}{c}\right)^{k-1} exp\left(-\left(\frac{(1+\rho\,l)\,v_i}{c}\right)^{k}\right), \tag{10}$$

in which:

$l = \dfrac{(v_r - v_i)}{v_i}$: Is the ratio of linear range of wind speed to cut-in wind speed.
$\rho = \dfrac{w}{w_r}$: Is the ratio of wind power output to rated wind power.

The WECS economic function, defined in (4), has the function-related penalty cost and reserve functions (10). Thus, the economic function of wind farms (Fw) is given by the sum of the linear cost (C_w), penalty cost (C_p), and reserve cost (C_r), defined as:

$$C_w(P_{w_i}) = d_i \cdot P_{w_i} \tag{11}$$

$$C_p\,(P_{w_i}) \;=\; k_{p_i}\left(\int_{P_{w_i}}^{w_{r_i}} w\,fW(w)\,dw - P_{w_i}\int_{P_{w_i}}^{w_{r_i}} fW(w)\,dw\right) \tag{12}$$

$$C_r\,(P_{w_i}) \;=\; k_{r_i}\left(P_{w_i}\int_0^{P_{w_i}} fW(w)\,dw - \int_0^{P_{w_i}} w\,fW(w)\,dw\right), \tag{13}$$

in which:

$C_w(P_{w_i})$: Linear cost function for the i generator, expressed in \$/MW.
$C_p(P_{w_i})$: Penalty cost function for the i generator, expressed in \$/MW.
$C_r(P_{w_i})$: Reserve cost function for the i generator, expressed in \$/MW.
d_i: Direct cost coefficient for the i generator, expressed in \$/MW.
P_{w_i}: Wind energy produced by the i generator, determined in MW.
w_{r_i}: Rated wind power of generator i, expressed in MW.
k_{p_i}: Penalty cost coefficient of generator i.
k_{r_i}: Reserve cost coefficient of generator i.

The model (1) is stochastic because the components of the (12) and (13) functions in WECS use wind speed as a random variable in their energy production, which is calculated by the probability function (10).

2.3. Processing Modular Terms of the Fe Function

With the insertion of the valve loading point function associated with a sinusoidal absolute value function, in the calculation of the economic function (2), which will be used in the formulation of the thermal, wind, economic, and environmental dispatch, the *Fe* becomes non-convex and non-differentiable. This makes it impossible to use the majority of classical and deterministic optimization methods to solve the problem.

A transformation based on Bazaraa, Sherali, and Shetty [32] is hence applied to the economic function (2), which is then rewritten as follows:

$$Fe = Fe_1 + Fe_2 \tag{14}$$

for

$$Fe_1 = \sum_{j=1}^{m} (Fe_1)_j \qquad and \qquad Fe_2 = \sum_{j=1}^{m} \mid (Fe_2)_j \mid$$

in which:

$$(Fe_1)_j = a_j P_{t_j}^2 + b_j P_{t_j} + cj$$
$$(Fe_2)_j = e_j \, sen \, (f_j \, (P_{t_j}^{min} - P_{t_j}) \,)$$

for $j = 1, 2, \cdots, m$.

From (14), an unconstrained problem (15) is considered, expressed as:

$$Minimize \ \sum_{j=1}^{m} (Fe_1)_j + \sum_{j=1}^{m} \mid (Fe_2)_j \mid . \tag{15}$$

Based on [32], the unconstrained problem (15) becomes a constrained problem, defined by:

$$\begin{aligned} Minimize \ & \sum_{j=1}^{m} (Fe_1)_j + \sum_{j=1}^{m} v_j \\ subject \ to \ & -v_j \leq (Fe_2)_j \leq v_j \\ & v_j \in \Re. \end{aligned} \tag{16}$$

The objective function of the problem (16) becomes a sum of a quadratic function and a linear one, and the sinusoidal function is rewritten and bounded into the constraints of the problem (16). The modular part of the objective function (15), defined by the constraint problem (16), is redefined, turning this problem into a constrained problem with a differentiable objective function. Considering WTEEDP (1), the reformulation of (15) and the constrained problem (16), which considers the insertion of a loading valve point (LVP) defined by (Fe_2) in (14), is termed WTEEDP—LVP. The multi-objective problem to be solved is hence expressed as:

$$
\begin{aligned}
Minimize \left\{ \sum_{j=1}^{m} (Fe_1)_j \; + \; \sum_{j=1}^{m} v_j \; + \; \sum_{i=1}^{n} Fw \, , \, \sum_{j=1}^{m} Fa \right\} \\
subject\ to \ \sum_{i=1}^{n} Pw_i + \sum_{j=1}^{m} Pt_j = D + L \\
(Fe_2)_j - v_j \; \leq \; 0 \\
(Fe_2)_j + v_j \; \geq \; 0 \\
0 \; \leq \; Pw_i \; \leq \; Pw_i^{max} \\
Pt_j^{min} \; \leq \; Pt_j \; \leq \; Pt_j^{max} \\
v_j \; \in \; \Re,
\end{aligned} \tag{17}
$$

in which:

- v_j is an auxiliary variable to represent the additional costs with valve point loading.

2.4. Methodology for Solving the Multi-Objective Problem

The proposed method used for model resolution (17) is the Weighted Goal Programming (described in Jones and Tamiz [22]) combined with the Progressive Bounded Constraints Method (WGPPBC), found in Dos Santos et al. [20] and Gonçalves et al. [21]. This strategy is used due to the difficulty in solving the proposed model (17), which involves convex functions (Fe_1) with non-convex constraints (Fe_2) in its domain, in relation to the absolute value sinusoidal function that occurs in the economic function (Fe), as seen in (2).

For the WTEEDP—LVP presented, based in Miettinen [33], the proposed WGPPBC strategy will be used to generate a set of single-objective sub-problems, determine the efficient solutions that approximate the Pareto optimal curve, and hence determine compromise solutions of interest to the decision-maker. The subproblems generated by the WGPPBC and WGP are solved by the computational package knitro, found in the Gams software.

To use the above methods, the following problems are defined:

$$
\left\{ \text{Minimize} \sum_{j=1}^{m} Fe + \sum_{i=1}^{n} Fw \ , \ \text{subject to the constraints of the problem (17)} \right\} \tag{18}
$$

and

$$
\left\{ \text{Minimize} \sum_{j=1}^{m} Fa \ , \ \text{subject to the constraints of the problem (17).} \right\} \tag{19}
$$

The problems (18) and (19) are used to determine the solutions Fa^{min}, $(Fe + Fw)^{min}$, Fa^{max}, and $(Fe + Fw)^{max}$, which are found as follows:

- The solution to problem (18) determines $(Fe + Fw)^{min}$, which is the minimum value of the cost objective, and Fa^{max}, the maximum value of the environmental objective.
- The solution to problem (19) determines Fa^{min}, which is the minimum value of the environmental objective, and $(Fe + Fw)^{max}$, the maximum value of the cost objective.

Note that the above methodology assumes a strict conflict between the economic and environmental functions. The ideal solution is defined by the values of $(Fe + Fw)^{min}$ of the problem (18) and Fa^{min} of the problem (19).

2.4.1. Progressive Bounded Constraint Method

In multi-objective problems, generally, the functions are conflicting, as in the presented case of the model (1), where the minimization of the costs of thermal and wind energy generation and the minimization of the pollutant emission are conflicting objectives.

In the case of WTEEDP—LVP, the cost function $(Fe + Fw)$ has become the single-objective function of the model, emphasizing the cost minimization, and the environmental function (Fa) is incorporated into its constraints, being assigned lower and upper limits corresponding to minimum and maximum emission levels, according to the N single-objective sub-problems defined in (21) for each subinterval I_k.

The PBC model will find, where existing, N efficient solutions, determined by considering each subinterval I_k, where $I_k = [Fa_k^{min}, Fa_k^{max}] \subset I$. The I subinterval is defined from the solutions of problems (18) and (19), that is, $I = [Fa^{min}, Fa^{max}]$.

1. Fa^{min} is the value obtained for Fa in the optimal solution (19).
2. Fa^{max} is the value obtained for Fa in the optimal solution (18).

Since the environmental function is used as a model constraint, then the I interval is subdivided into N equally spaced subintervals, $k = 0, 1, ..., N-1$, and considering $\Delta = \dfrac{Fa^{max} - Fa^{min}}{N}$, we have:

$$Fa_k^{min} = Fa^{min} + k\,\Delta \quad \text{and} \quad Fa_k^{max} = Fa^{min} + (k+1)\,\Delta, \tag{20}$$

in which: $Fa_0^{min} = Fa^{min}$ and $Fa_{N-1}^{max} = Fa^{max}$.

The values of Fa_k^{max} and Fa_k^{min} represent, respectively, new upper and lower bounds of the Fa function, which will be bounded into single-objective sub-problems (21). According to Dos Santos et al. [20] and Gonçalves et al. [21], to obtain a better distribution of points from the Pareto optimal curve, a greater amount of subintervals of the I set associated with the Fa function must be used. With these considerations, the set of single-objective sub-problems given by PBC is defined in (21).

$$\begin{aligned}
\text{Minimize} \qquad & \sum_{j=1}^{m} (Fe_1)_j \;+\; \sum_{j=1}^{m} v_j \;+\; \sum_{i=1}^{n} Fw \\
\textit{subject to} \quad & \sum_{i=1}^{n} Pw_i + \sum_{j=1}^{m} Pt_j = D + L \\
& Fa_k^{min} \le \sum_{j=1}^{m} Fa \le Fa_k^{max} \\
& (Fe_2)_j - v_j \;\le\; 0 \\
& (Fe_2)_j + v_j \;\ge\; 0 \\
& 0 \;\le\; Pw_i \;\le Pw_i^{max} \\
& Pt_j^{min} \;\le\; Pt_j \;\le Pt_j^{max} \\
& v_j \;\in\; \Re,
\end{aligned} \tag{21}$$

in which Fa_k^{max} and Fa_k^{min} are defined in (20).

The objective function of the problem is given by $Fe + Fw$, with Fe and Fw, defined respectively in (2) and (4). The constraints must meet the demand of thermal and wind operators, as well as their operating limits, which were presented in (17). In (21), we add the Fa environmental function bounding constraint defined in (3), considered for lower emission limits $Fa_k^{min} \in I_k$ and upper emission limits $Fa_k^{max} \in I_k$, for $k = 0, 1, ..., N-1$.

A set of Pareto efficient solutions is found through the resolution of each sub-problem to give a good representation of the Pareto optimal curve.

2.4.2. Weighted Goal Programming

In the proposed model, the goal target values are set at their ideal values, found by (18) and (19). These are not achieved simultaneously for the same solution because the objective functions are conflicting for the problem (17). Thus the ideal, or utopian, solution is aimed for, which is a valid form of the weighted goal programming variant used in Jones and Tamiz [22].

Preferential weights w_1, w_2, w_3, and w_4 are used, where $w_1 + w_2 + w_3 + w_4 = 1$ to assist in determining solutions belonging to the Pareto optimal curve. The achievement function (22) aims to objective minimize the unwanted deviations of variables below or above the established goals, respectively, by n_1, n_2, p_1, and p_2. In practice, two of these deviational variables are redundant due to the usage of ideal goal values, but they are included for the sake of completeness. In addition to the constraints on meeting demand from wind and thermal operators and the operating limits defined in (17), other constraints were inserted into the problem relative to multi-objective functions $(Fe + Fw)$ and (Fa) together with the difference between the lower and upper deviational variables, which are considered to verify the best proximity to the established goal, in an equality constraint. Note that $n_t \geq 0$ and $p_t \geq 0$ for $t = 1, 2$, but these are complementary to each other, that is, $n_t > 0$ so $p_t = 0$ and vice versa.

The achievement function used for model resolution (17), associated with the weighted goal programming technique defined in Jones and Tamiz [22], allows direct compensation for all deviational variables by putting them in a weighted, normalized form. The mathematical modeling of the model (17) considering the weighted goal programming technique is defined in (22).

$$
\begin{aligned}
\text{Minimize} \quad & \frac{w_1\, p_1}{(Fe + Fw)^{min}} + \frac{w_2\, n_1}{(Fe + Fw)^{min}} + \frac{w_3\, p_2}{Fa^{min}} + \frac{w_4\, n_2}{Fa^{min}} \\
\text{subject to} \quad & \sum_{i=1}^{n} Pw_i + \sum_{j=1}^{m} Pt_j = D + L \\
& \sum_{j=1}^{m} (Fe_1)_j + \sum_{j=1}^{m} v_j + \sum_{i=1}^{n} Fw + n_1 - p_1 = (Fe + Fw)^{min} \\
& \sum_{j=1}^{m} Fa + n_2 - p_2 = Fa^{min} \\
& (Fe_2)_j - v_j \leq 0 \\
& (Fe_2)_j + v_j \geq 0 \\
& 0 \leq Pw_i \leq Pw_i^{max} \\
& Pt_j^{min} \leq Pt_j \leq Pt_j^{max} \\
& v_j \in \Re \\
& n_1, n_2, p_1, p_2 \geq 0,
\end{aligned}
\tag{22}
$$

in which

w_1, w_2, w_3 and w_4 are the weights of the objectives, where $w_1 + w_2 + w_3 + w_4 = 1$;
$Fe + Fw^{min}$ and Fa^{min} are the goals to be achieved, determined in (18) and (19);
n_1 and n_2 are the deviational variables lower than the established goal, associated respectively with the objective functions $Fe + Fw$ and Fa;
p_1 and p_2 are the deviational variables higher than the established goal, associated respectively with the objective functions $Fe + Fw$ and Fa, which are being minimized in the achievement function.

2.4.3. Weighted Goal Programming with Progressive Bounded Constraints (WGPPBC)

The weighted goal programming with progressive bounded constraints (WGPPBC) technique is a combination of PBC and the WGP technique, and arose due to the difficulty presented in the PBC resolution in determining the maximum points for the defined single-objective sub-problems. This method is seen in (17) due to the absolute value sinusoidal function, which occurs in the economic function (Fe), with the same idea presented in the transformation defined in Section 2.3. Concerning problem (16), the sinusoidal function (Fe_2) was treated in the same way in this new combined technique. The transformation used in WTEEDP—LVP resolution was presented in the unconstrained problem (15), turning it into a constrained problem (16).

The WTEEDP—LVP formulation with the new WGPPBC technique, considering the equivalent model formulation (17), is given by:

$$
\begin{aligned}
\text{Minimize} \quad & \frac{w_1\, p_1}{(Fe+Fw)^{min}} + \frac{w_2\, n_1}{(Fe+Fw)^{min}} + \frac{w_3\, p_2 + w_4\, n_2}{\frac{1}{2}(Fa^{min}+Fa^{max})} \\
\text{subject to} \quad & \sum_{i=1}^{n} Pw_i + \sum_{j=1}^{m} Pt_j = D + L \\
& \sum_{j=1}^{m} (Fe_1)_j + \sum_{j=1}^{m} v_j + \sum_{i=1}^{m} Fw + n_1 - p_1 = (Fe+Fw)^{min} \\
& \sum_{j=1}^{m} Fa + n_2 = Fa_k^{max} \\
& \sum_{j=1}^{m} Fa - p_2 = Fa_k^{min} \\
& 0 \le Pw_i \le Pw_i^{max} \\
& Pt_j^{min} \le Pt_j \le Pt_j^{max} \\
& v_j \in \Re \\
& n_1, n_2, p_1, p_2 \ge 0,
\end{aligned}
\tag{23}
$$

where all terms considered in (23) are defined in (17) and (22).

The WTEEDP—LVP is solved using the WGPPBC technique, which defines the single-objective sub-problems given in (23), to determine the efficient solutions and values that make up the Pareto optimal curve from the multi-objective problem defined in (17). The weighted goal programming technique defined in (22) is then used to determine decision-maker-preferred solutions whose values also belong to the Pareto optimal curve.

To solve the proposed problems, power generation simulations were performed without and with the use of wind generators for cases in which the system presents only the thermal units, and later, in each case, a wind unit is inserted into the generation system with the purpose of verifying which wind farm will be chosen to be installed. The resolutions of the single-objective sub-problems defined in (23) by the WGPPBC technique and in (22) by the WGP technique are performed through Gams software using the knitro computational package. The results obtained are presented in Section 3.

3. Results

In order to analyze the importance of wind power production in achieving sustainability of power systems, it is necessary to compare the quantity of emissions that the energy system would produce without the insertion of a wind farm and, later, to verify how the insertion of these plants would help in reducing these emissions.

Three possible variants of the wind unit were investigated, which present the same average wind speed, but with different parameters of the Weibull probability density function given by c and k. From the results obtained, it is determined which wind farm unit will be chosen to be installed according to the objectives of the sustainable dispatch problem.

The economic and environmental dispatches related to thermal units are represented by objective functions related to the cost of fossil fuel burning and the emission of pollutants, respectively in dollars per hour (\$/h) and kilograms per hour (Kg/h), with constraints of the demand fulfillment and the lower (Pt_i^{min}) and higher (Pt_i^{max}) operating limits of the thermal unit generation. The following parameters are set pertaining to the wind units: The maximum limit of the wind farm unit (Pw_i^{max}), direct cost coefficient (d), penalty cost coefficients (K_p) and reserve cost (K_r) and wind speed limiting associated with wind power turbines (v_i, v_r and v_0). The resulting models are solved using the WGPPBC technique, as described in the previous section.

The points that make up the Pareto optimal curve are the values found for the cost function $(F_e + F_w)$ and for the environmental function (F_a) related to the efficient solutions determined by WGPPBC for each single-objective sub-problem defined in (23). The solutions found to the sub-problems by the weighted goal programming technique are termed compromise solutions, which also belong to the Pareto optimal curve and are found by assigning different values to the weights w_1, w_2, w_3, and w_4 from the model criterion function (22) by the package knitro. Given the set of solutions found, it is determined which of them is the nearest to the ideal solution, which will be used by the decision-maker to compare the results obtained for each case to be explored.

The following concepts are represented graphically in order to visualize the resulting solutions.

1. Ideal solution ($\times$): Problem lexicographic values $((Fe + Fw)^{min}, Fa^{min})$ found by solving problems (18) and (19).
2. Efficient solutions ($*$): Solutions of the subproblems generated by the WGPPBC technique (23), which determine the values that make up the Pareto optimal curve.
3. Goal programming solutions ($\circ$): The problem determined solutions (22) generated by the WGP technique, determined from the w_1, w_2, w_3, and w_4 considered.
4. The goal programming solution selected by the decision-maker (indicated with a square), including the proximity to the ideal point in their reasoning.

System of 30 Bar—6 Thermal Generators

The data for the resolution of WTEEDP—LVP associated with the 30—bar system were used. The cost coefficients of the thermal units presented in Table A1 are found in Gonçalves et al. [21] and Ravi, Chakrabarti, and Choudhuri [34]. The data reported regarding the wind farm units given in Table A2 are found in CRESESB [35] and ONS [36]. Using the data from these established literature sources ensures the relevance and adequacy of the data for the purpose of investigating the addition of wind farm units into a thermal system.

The cases that will be investigated are presented as follows:

- Case A: Three thermal generators.
- Case B: Three thermal generators and wind farm unit 1.
- Case C: Three thermal generators and wind farm unit 2.
- Case D: Three thermal generators and wind farm unit 3.

The demand of power generation production is 283.4 MW.

Regarding the cases to be investigated, note that in case A, three thermal generators are considered without the inclusion of wind generators. In cases B, C, and D, the same thermal generators are considered, however, with the insertion of only one wind farm unit in each case respectively, the wind farm units 1, 2 and 3. This is done to assess which of the wind farm units will be installed according to the values assigned in the economic and environmental functions, comparing the results obtained in case A, where there is no insertion of the wind farm unit.

Figures 1–4 present the efficient solutions of single-objective sub-problems (23) obtained utilizing the WGPPBC strategy.

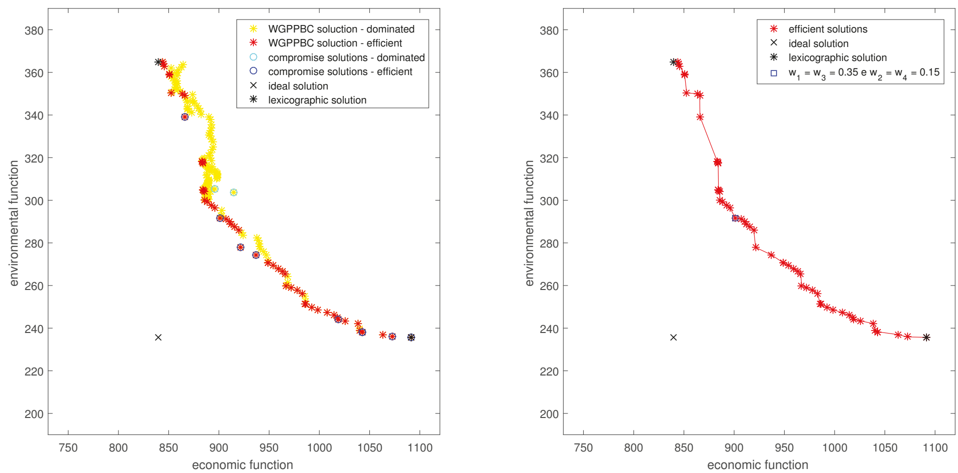

Figure 1. Results of the wind–thermal economic and environmental dispatch problem with insertion of a loading valve point (WTEEDP—LVP)—Case A.

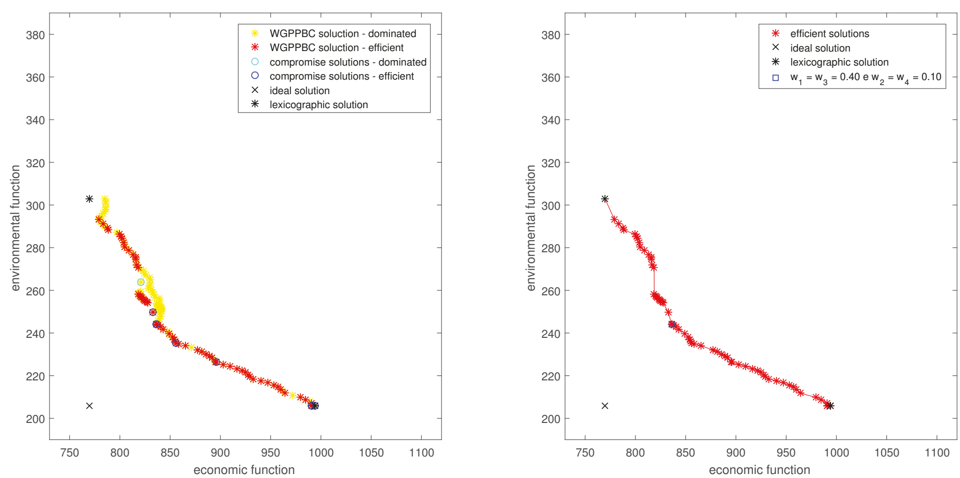

Figure 2. Results of the wind–thermal economic and environmental dispatch problem with insertion of a loading valve point (WTEEDP—LVP)—Case B.

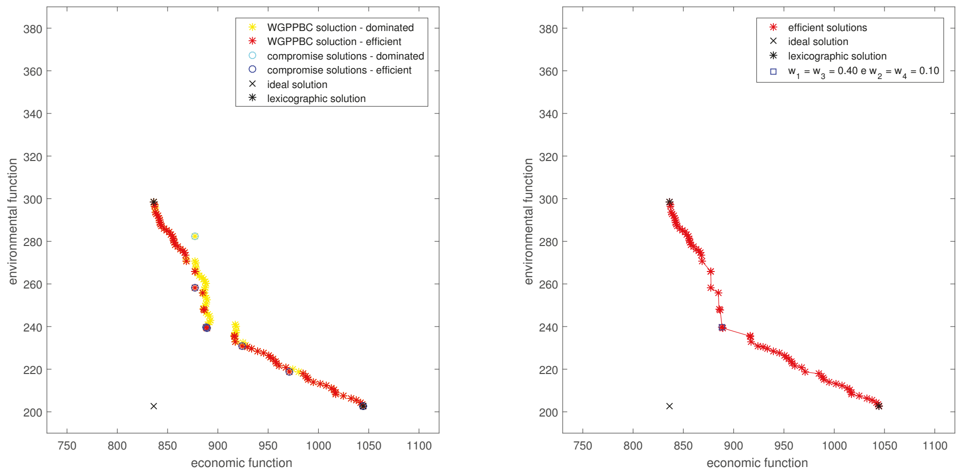

Figure 3. Results of the wind–thermal economic and environmental dispatch problem with insertion of a loading valve point (WTEEDP—LVP)—Case C.

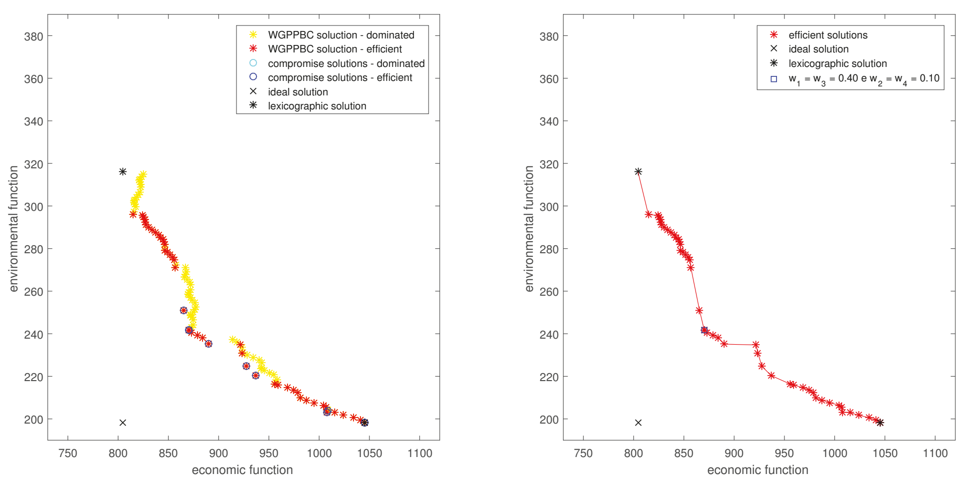

Figure 4. Results of the wind–thermal economic and environmental dispatch problem with insertion of a loading valve point (WTEEDP—LVP)—Case D.

The compromise solutions represented by ○ and the square in Figures 1–4 were found by the weighted goal programming technique using the weights w_1, w_2, w_3, and w_4, where $w_1 + w_2 + w_3 + w_4 = 1$, with $w_1 = w_3$ and $w_2 = w_4$. The *Fe* function is non-convex and non-differentiable, so in WTEEDP—LVP, some compromise solutions can be dominated, and the representation in the graph is the ○ symbol in light blue.

Figure 5 represents the Pareto optimal curve containing the efficient and compromise solutions determined for each case.

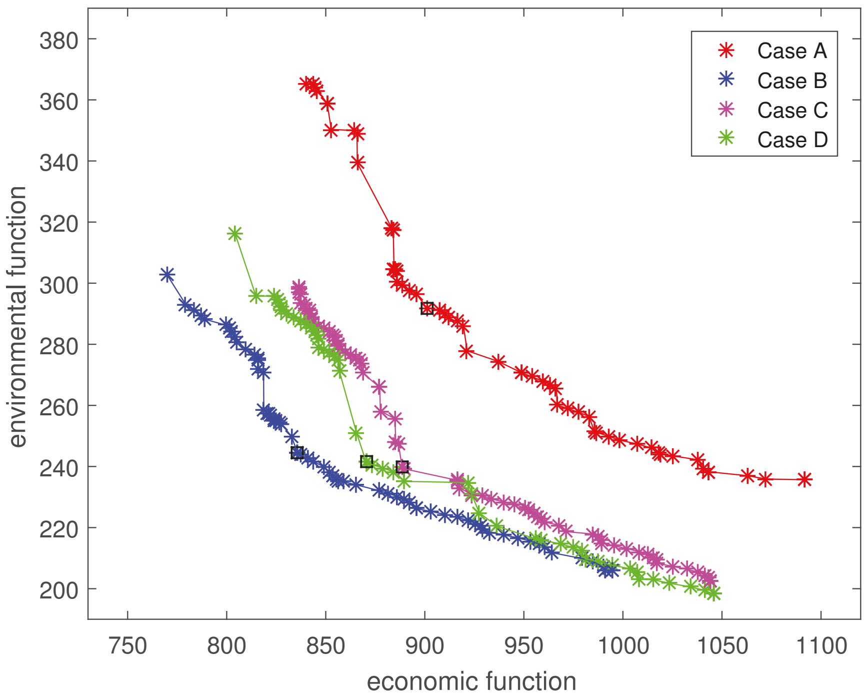

Figure 5. Results of the wind–thermal economic and environmental dispatch problem with insertion of a loading valve point (WTEEDP—LVP).

According Figure 5, we can see how the variation of the economic and environmental functions occurs for each case studied. From these results, we can verify among cases B, C, and D what the best decision related to the wind farm unit to be installed is in comparison with the results obtained in case A, considering the interest of the decision-maker in obtaining the reduction of the cost associated with the economic function $(Fe + Fw)$ or reduction of the emission associated with the environmental function (Fa).

Table 1 presents the goal-exceeded values for each case (A, B, C, and D), where only the variables with positive deviations assume values greater than zero.

Table 1. Deviation variable values from weighted goal programming (WGP) for cases A, B, C, and D.

CASE	n_1	n_2	p_1	p_2
A	0	0	61.115	56.072
B	0	0	66.131	38.294
C	0	0	52.186	37.342
D	0	0	65.960	43.389

The values presented in Table 1 show how much the values found for the $(Fe + Fw)$ and Fa functions of the solution chosen by the decision-maker are above the set goal.

For case A, where we do not have the wind farm insertion, according to the deviation p_1, the value of the $Fe + Fw$ function exceeded 7.27% of the goal set ($(Fe + Fw)^{min} = 840.08$); according to the deviation p_2, the value of Fa exceeded 23.79% of the goal set ($(Fa)^{min} = 235.69$). For the cases where we have the wind farm insertion in case B, according to the deviation p_1, the function $Fe + Fw$ exceeded 8.59% ($(Fe + Fw)^{min} = 769.85$) and, according to the deviation p_2, Fa exceeded 18.59% of the goal set ($(Fa)^{min} = 205.97$). In case C, according to the deviation p_1, the value of $Fe + Fw$ function exceeded 6.24% ($(Fe + Fw)^{min} = 863.31$), and according to the deviation p_2, the value of Fa exceeded 18.44% of the goal set ($(Fa)^{min} = 202.55$). In case D, according to the deviation p_1, the value of the $Fe + Fw$ function exceeded 8.20% ($(Fe + Fw)^{min} = 804.35$), and according to the deviation p_2, the value of Fa exceeded 21.89% of the goal set ($(Fa)^{min} = 198.24$). It is the decision-maker who verifies which of the solutions found are satisfactory and meets the production interest of the power plant, according to the results obtained by the proposed problem.

For determining which wind farm will be deployed, an analysis was made of the solutions chosen by the decision-maker for each case investigated. The comparison of the values found was made in relation to the solution obtained by exploring the WGP technique, which is the solution that is nearest to the ideal solution. Table 2 presents the solution found in case A with the weights $w_1 = 0.35$ and $w_2 = 0.15$, and for cases B, C, and D with the weights $w_1 = 0.40$ and $w_2 = 0.10$, the weight values for each case are inserted in the Table A3. According to the w_1 weights defined for all cases, greater emphasis was given to the $(Fe + Fw)$ objective, thus giving preponderance to the economic objective.

Table 2. Value of the cost and emissions found by WGP for cases A, B, C, and D.

CASE	Fe	Fw	$Fe + Fw$	Fa	Emission Reduction	Cost Reduction
A	901.19	0.00	901.19	291.76	-	-
B	799.16	36.82	835.98	244.23	16.29%	7.24%
C	779.67	108.83	888.50	239.89	17.78%	1.41%
D	749.52	120.79	870.31	241.63	17.18%	3.43%

The values presented in Table 2 show that the insertion of wind power into the power system reduces pollutant emissions. With the insertion of wind farm unit 1 (case B), there was a reduction of 47.53 Kg/h with relation to the emission of pollutants found without the insertion of wind farm units (Case A), corresponding to a reduction of 16.29% in the emission of polluting gases through the burning of fossil fuels. In case C, when inserting the wind farm unit 2, the reduction was 51.87 Kg/h compared to case A, referring to 17.78%, and in the implantation of wind farm unit 3 (case D), the reduction was 50.13 Kg/h, corresponding to the 17.18% reduction in pollutant emissions relative to case A.

Comparing the results obtained in Table 2 for cases B, C, and D as compared to case A, if the decision-maker's interest is to obtain the best pollutant reduction, the option would be to install wind farm 2, corresponding to case C, with a 17.18% emission reduction and with the lowest operating cost reduction, which is 1.41%. On the other hand, if the option were to improve cost reduction, the choice would be the implantation of wind farm 1 for case B, with 7.24% cost reduction and 16.29% polluting reduction, which is the worst result for emission reduction. An intermediate and balanced choice would be to deploy wind farm 3 in case D, respectively, with an emission reduction of 17.18% and cost reduction of 3.43%.

Therefore, from the results obtained, it can be seen that the addition of a wind farm in all investigated cases (B, C, and D) ensures the reduction of pollutant emissions and operating costs when compared with case A without the insertion of wind farm. The results show the importance and feasibility of exploiting the wind energy in the power generation system in terms of improving the overall sustainability of power systems.

4. Conclusions

This paper has implemented a novel methodology based on a combination of goal programming and the progressive bounded constraints as well as weighted goal programming in order to resolve the economic and environmental dispatch problem for a combination of thermal and wind power units. This has allowed the quantification of the benefits of adding wind power units into a conventional power system. The results in Figures 1–5 show that:

1. There is a clear and measurable benefit for both environmental and economic sustainability objectives of adding wind units into an existing solely thermal unit of a power generation system with respect to the modeled dispatch problem.
2. There is a measurable trade-off between the levels of benefits on the economic and environmental sustainability objectives when inserting wind units into an existing solely thermal unit of a power generation system with respect to the modeled dispatch problem.
3. The level of benefits gained and economic–environmental trade-offs are not necessarily linear, as can be seen by the trade-off curves of Figures 1–5, and are dependent on the characteristics of the individual power units modeled.

The above results should give encouragement to managers and stakeholders of solely thermal power systems to consider inserting wind-based units into their systems if the conditions allow. Equally, designers of new systems should consider the appropriate inclusion level of wind power in their systems. In both cases, this paper has presented a methodology that can be used to give a quantification of the environmental and economic benefits of wind power inclusion.

This paper has examined one pair of energy sources (thermal and wind) with two sustainability objectives (economic and environmental). Potential further work could involve the addition of more conventional and intermittent energy sources as well as additional objectives.

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Appendix A

The cost coefficients of the generating units that are presented in Table A1 can be found in Gonçalves et al. [21] and Ravi, Chakrabarti, and Choudhuri [34].

Table A1. Thermal generator data.

Unit (t)	Pt^{min} (MW)	Pt^{max} (MW)	Economic Function a	b	c	e	f	Environmental Function α	β	γ
1	50	200	0.00375	2.00	0	22.0310	0.083776	0.00419	0.32767	13.85932
2	20	80	0.01750	1.75	0	10.5000	0.209440	0.00419	0.32767	13.85932
3	15	50	0.06250	1.00	0	8.8594	0.359040	0.00683	−0.54551	40.26690
4	10	35	0.08340	3.25	0	8.7538	0.502650	0.00683	−0.54551	40.26690
5	10	30	0.02500	3.00	0	4.0000	0.628320	0.00461	−0.51116	42.89553
6	12	40	0.02500	3.00	0	6.0200	0.448800	0.00461	−0.51116	42.89553

The wind farm data that are given in Table A2 can be found in CRESESB [35] and ONS [36].

Table A2. Data from wind generators.

Unit (i)	Form Factor (k)	Scale Factor (c)	Pw^{max} (MW)	Direct Cost (d)	Initial Speed (v_i)	Rated Speed (v_r)	Cutting Speed (v_0)	Penalty Cost Coefficient (k_p)	Reserve Cost Coefficient (k_r)
1	2.26	8.47 m/s	32.50	$0.8	5 m/s	15 m/s	25 m/s	0.95	0.05
2	4.02	8.27 m/s	36.80	$1.0	5 m/s	20 m/s	25 m/s	0.70	0.30
3	3.50	8.34 m/s	42.50	$0.6	5 m/s	15 m/s	25 m/s	0.85	0.15

The values of the weights used in each case are given in Table A3.

Table A3. The weights used in each case.

	w_1	w_2	w_3	w_4
Case A	0.35	0.15	0.35	0.15
Case B	0.40	0.10	0.40	0.10
Case C	0.40	0.10	0.40	0.10
Case D	0.40	0.10	0.40	0.10

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sustainability

Article

Quantifying the Sustainability of Products and Suppliers in Food Distribution Companies

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Abstract: Supplier evaluation is a relevant task of supply chain management where multicriteria methods make great contributions to manufacturing industries. This is not the case in food distribution companies, which have a key role in providing safe and affordable food to society. The purpose of this research is to measure the sustainability of products and suppliers in food distribution companies through a multiple criteria approach. Firstly, the system proposed provides indicators to qualify products and assess the food quality, using the compensatory Multi-Attribute Utility Theory (MAUT) model. Secondly, these indicators are included in supplier evaluation, which takes economic, environmental, and social criteria into account. MAUT and Preference Ranking Organisation Method for Enrichment Evaluation (PROMETHEE), a non-compensatory method, are used for supplier evaluation. This approach has been validated for fresh food in a supermarket chain, mainly using historical data. Partial indicators, such as food safety scores, together with global indicators of suppliers, inform the most appropriate decisions and the most appropriate relations between companies and providers. Poor performance in food safety can lead to the disqualification of some suppliers. MAUT is good for qualifying products and is easy to apply at the operational level in logistic platforms, while PROMETHEE is more suitable for supplier segmentation, as it helps to identify supplier strengths and weaknesses.

Keywords: supplier evaluation; supplier segmentation; multi-attribute utility theory; preference ranking organisation method for enrichment evaluation; quality indicator; food safety; fresh food; sustainable supply chain; multicriteria

1. Introduction

In recent decades, sustainability has been an increasing concern for a society that involves everything from countries to companies and consumers. Sustainability can be assessed in relation to different scopes, such as a sector, supply chain, company, supplier, and/or product. Many decision-making problems deal with this concept from different perspectives. Life Cycle Assessment (LCA) is a common approach in the scientific literature dealing with product sustainability evaluation. Nevertheless, LCA is not an appropriate tool to support decision making in Sustainable Supply Chain Management (SSCM) [1]. The Multiple Criteria Decision Making (MCDM) approach is suitable to aggregate different dimensions of sustainability and provides a wide range of methods, which allow us to tackle a wide range of issues and support decision making [2].

Literature offers a huge number of research works focused on supplier evaluation, as well as well-structured reviews on this topic. The main approaches are Data Envelopment Analysis (DEA), Analytic Hierarchy Process (AHP), Analytic Network Process (ANP), Technique for Order Performance by Similarity to Ideal Solution (TOPSIS), Simple Multi-Attribute Rating Technique (SMART), Preference

Ranking Organisation Method for Enrichment Evaluation (PROMETHEE), ELimination Et Choix Traduisant la REalité (ELECTRE) and Linear, Mixed Integer, Goal, and Multiobjective Programming. The applications are concentrated in various manufacturing sectors, such as the automotive, electrical, and electronics sectors, among others [3–10].

The SSCM concept involves integrating all three dimensions of sustainability. Nevertheless, published research has mainly been focused on economic and environmental criteria, with scarce contributions that included social criteria. It is also interesting to point out that research has solved the supplier selection problem for one product only, although this situation is not frequent [11–19]. In practice, companies buy several products from several suppliers and the same supplier provides several products. Moreover, the majority of case studies used data based on opinions, judgements, and/or direct ratings from experts or managers [20–22]. There is a proposal for supplier evaluation for several products, applied to the food industry, in which decision making integrates historical data and expert knowledge [23].

There are many applications of MCDM methods to supplier evaluation for selection and segmentation in manufacturing companies, some in food industries [6–20]. Nevertheless, this situation contrasts with the lack of proposals for the food distribution business, such as supermarket chains. The food supply chain is different from other supply chains when it comes to sustainable management, due to the continuous change in the quality of products until the point of final consumption. In addition to sustainability, consumers demand quality and safety as important food attributes [24,25]. Lau et al. (2017) carried out the only research that applies MCDM to fresh food supplier evaluation in a supermarket chain in Australia. They applied Fuzzy AHP to obtain the weights of criteria, ELECTRE to rank the supplier performance with respect to food safety, as a non-compensatory criterion, and TOPSIS to rank suppliers qualified previously by the safety criterion [26]. Evaluating food suppliers from a sustainable perspective requires the definition of specific criteria and indicators, such as those that are applied to measure food safety [27]. This criterion can be included in the social dimension [3], although some authors propose defining food sustainability based on five dimensions: social, environmental, economic, health and ethical [28].

The aim of this research is to measure the sustainability of products and suppliers in food distribution companies through a multiple criteria approach. For this purpose, a decision support system was designed in order to first obtain product indicators, which allow the companies both to accept/reject products and to assess the quality of food. These product indicators are subsequently included in a global supplier evaluation from a sustainable perspective, which takes into account economic, environmental, and social criteria.

The main contribution of this paper is related to product and supplier evaluation in the last part of the fresh food supply chain, based on multiple criteria techniques, integrating historical and objective data on product and supplier performance rather than the judgements and direct rating from managers alone. This approach also allows us to classify suppliers by analyzing the historical and reliable indicators needed in a decision support system to inform decision making at operational, tactical, and strategic levels. This research innovates in proposing and validating a model to evaluate an important part of the fresh food supply chain from a sustainable perspective, based on historical and objective data. To our knowledge, this is a new and original proposal that allows us to generate information useful for making sustainable decisions on a regular basis in supermarket chains. This supply chain differs from others due to the change in the quality of products until they are consumed. In addition, new social criteria related to food safety are proposed in a novel and unified approach to dealing with sustainable fresh food and supplier evaluation in distribution companies, such as supermarket chains.

The rest of the paper is organized as follows: Section 2 briefly presents the methodology used and the decision support system proposed for food and supplier evaluation, which is based on several compensatory and non-compensatory multiple criteria techniques. The system proposed has been validated in a real company, a supermarket chain, as explained in Sections 3 and 4. In Section 3, criteria related to fresh food (fruits) are defined and their utility functions established in order to obtain quality indicators for products by applying Multi-Attribute Utility Theory (MAUT) methodology. The case study allows validation of the model, which is based on data about different varieties of yellow peach and from several suppliers. Section 4 presents the results of sustainable evaluation of suppliers, by integrating quality indicators of products with food safety, logistic, commercial, and environmental criteria. This sustainable evaluation of suppliers is carried out through PROMETHEE and MAUT. Outcomes from these two methodologies are compared, highlighting their key strengths and weaknesses. Finally, a discussion of results and conclusions is presented in the last two sections, respectively.

2. A Multiple Criteria System for Sustainable Evaluation of Food and Suppliers in Distribution Companies

Multiple Criteria Decision Making (MCDM) techniques stand out among the huge volume of literature focused on supplier evaluation [3,5,6,8]. When sustainability is taken into account, the MCDM approach is essential to integrate conflicting objectives in the analysis appropriately. Although there is quite a number of well-established methods, selection of the most suitable is a relevant issue. The nature of the real problem to be solved, data availability and type (qualitative/quantitative), uncertainty and decision makers, as well as the chance of success in actual implementation are some of the basic issues to consider. In addition, real problem solving often requires innovative contributions in developing models for decision making.

The system proposed to evaluate fresh food and suppliers is based on at least two multiple criteria methods: MAUT and PROMETHEE, which are adequate and meet the needs for sustainable decision making in fresh food supply chain management. On the one hand, MAUT is easier for managers and decision makers in companies to understand and apply than PROMETHEE. On the other, MAUT is a compensatory method and PROMETHEE is non-compensatory, which is essential in aspects such as food safety, in addition to providing other advantages. For a detailed explanation of both methods, see Belton and Stewart [29]. The seminal work of Keeney and Raiffa [30] contributed the foundations and operational mechanics of MAUT. In addition, Brans and Mareschal [31] provides all versions of the PROMETHEE method, which has been applied to many fields [32,33], but only some articles to supply chain management [20,23,34–36]. AHP is the discrete multiple criteria method most applied on this topic so far, to both elicit weights of criteria and select suppliers, with a fuzzy version also used to deal with uncertainty [4,5,8,37,38]. In contrast, MAUT barely appears in the literature, although it is appropriate for qualifying products and suppliers [3,23].

Figure 1 shows the flowchart of the multiple criteria system for sustainable evaluation of food and suppliers in distribution companies proposed in this research. The first step consists of defining product categories, such as fruits, vegetables or meat. Then, focused on a specific category of homogenous products, the second step is to establish the evaluation criteria for products and suppliers. In food distribution companies, the departments involved are quality, purchasing and logistics, among others, depending on organisational structure. The weights of criteria play a very important role in many MCDM methods, and in particular in MAUT and PROMETHEE. Thus, the weights should take the company objectives and strategy into account. There are several ways to assign the weights of criteria. Determining weights by consensus among managers from the main departments or management board involved is one proposal that increases the real implementation of results in decision making. The AHP method, another multiple criteria approach, provides a robust mechanism to elicit the criteria weight collaboratively [39–41].

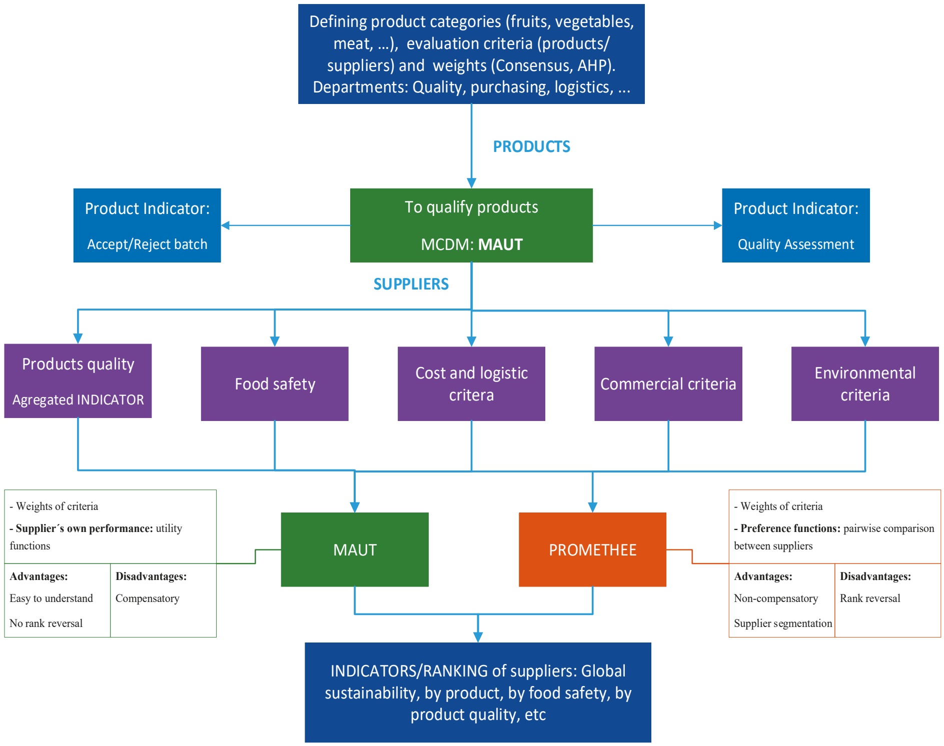


Figure 1. Flowchart of multiple criteria system for sustainable evaluation of food and suppliers in distribution companies.

After defining the criteria and grouping them in a hierarchy, as well as determining their weights, the second step is to qualify products. Food distribution companies have logistic platforms where products are checked to decide whether to accept or reject them according to conformity to specifications following established protocols. MAUT is the multiple criteria method to qualify and evaluate the quality of products. Therefore, the values of the criteria for each product are required, as well as the utility function for each criterion. Experts provide the information needed to draw up the specific utility functions. The global score of an alternative obtained by MAUT depends on its own performance, while the score from PROMETHEE is based on the pairwise comparisons among alternatives. As the quality of a product only depends on its performance according to the criteria, PROMETHEE is not applicable in this phase, as an objective quality of a product is not related to the quality of other products.

The third step is supplier evaluation, as shown in Figure 1. The scores of products provided by suppliers to assess are aggregated and then, together with other groups of criteria, considered for supplier evaluation. These additional criteria are food safety, cost and logistical criteria, commercial criteria, and environmental criteria. Food safety is a social criterion with an increasingly important role in the food supply chain, which can be measured by using sub criteria. The same applies for other criteria of suppliers, as shown in the case study in Section 4.

Global indicator of suppliers and their ranking are obtained by applying MAUT and PROMETHEE. Both have strengths and weaknesses, as they show complementary perspectives of the evaluation. Both require the weights of criteria; MAUT needs the utility functions that measure the supplier's own performance, while PROMETHEE uses pairwise comparison between suppliers through preference functions. Being easy for managers to understand is one of the main advantages of MAUT. In addition, it does not present the rank reversal problem, while PROMETHEE does. The compensatory nature of MAUT is its principal disadvantage, whereas the outranking method PROMETHEE is a non-compensatory approach. This is linked with the more discriminant power of the latter, which allows a segmentation mechanism that is very useful in supply chain management. Finally, this system provides indicators of suppliers by product, by food safety, as well as segmentation of suppliers by specific criteria, which is essential for decision making about the best relationship between the company and the supplier, such as for disqualifying suppliers, partnerships, and long-term contracts.

3. Results of the Quality Evaluation of Products

The multiple criteria approach explained in the previous section was applied to evaluate fresh fruits and suppliers in a supermarket chain with 740 stores located in Spain in order to improve the operations management of the company. This section shows the indicators of the quality of yellow peach provided by suppliers in the whole season from May to October 2018, whose data distribution from controls in the logistic platform is in Table 1. There are 10 varieties of yellow peach from six suppliers.

Table 1. Data distribution of yellow peach specifications by suppliers and varieties. Season 2018.

Variety	Suppliers						
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**Total**
Amarillo de Agosto				30	20		50
Babygold		20					20
Calante					10		10
Cinca			40				40
DIANA 0	40						40
GC 58			30	30	110		170
Miraflores		80		100	60		240
Poblet						19	19
Romea				100			100
Yellow stone		10					10
Total	40	110	70	260	200	19	699

Following a protocol, the company carries out regular inspections and measures the conformance to specification through three characteristics from ten pieces per batch: the quantity of sugars (Brix degrees), firmness (kg/cm^2) and size (mm). Due to the large amount of data, Figure 2 only shows some of them, together with minimum and maximum values for these specifications (supplementary material provides complete data). Brix degrees should be 9 as the minimum level to be acceptable, firmness should be between 2 and 5 kg/cm^2, and peach size between 65 and 80 mm. Based on the compliance level, yes/no for each characteristic, the company assigns a 1/0 indicator, respectively. The global indicator for the fruit inspected is 1 when the three specifications have a value of 1, and zero otherwise. If more than 20% of the fruits score zero, then the batch is rejected. This procedure does not assess the fruit quality. Therefore, it does not distinguish among peaches with minimum, maximum or optimum firmness, which is a criterion whose performance changes over time until the fruit is consumed. The system proposed in the previous section overcomes this weakness by applying a multicriteria approach to decide whether to accept/reject the fruit batch and gauge the product quality. The latter should provide important data for supplier evaluation.

The evaluation table used to apply MAUT and obtain a robust indicator for peach quality was built with data shown in Figure 2 and the supplementary material. In addition to the evaluation table, MAUT needs the weights of criteria, as shown in Figure 3, which were set by consensus in the quality department.

Product ID	Brix Min 9 degrees	Firmness 2-5 kg/cm²	Size 65-80 mm
YPJNC105YES2	11	2.8	64
YPJNC106YES2	11	2.8	65
YPJNC107YES2	11	2.8	66
YPJNC108YES2	10	3.2	66
YPJNC109YES2	11	2.8	66
YPJNC110YES2	12	3.5	65
YPJNC201CIS3	11	2	73
YPJNC202CIS3	11	2.8	69
YPJNC203CIS3	11	2.3	70
YPJNC204CIS3	9	3.2	70
YPJNC205CIS3	11	1.9	71
YPJNC206CIS3	8	2.6	72
YPJNC207CIS3	12	2.8	70
YPJNC208CIS3	11	3	71
YPJNC209CIS3	10	2.7	71
YPJNC210CIS3	11	2.7	71
YPJLC101ROS4	14	2.3	69
YPJLC102ROS4	12	3.6	68
YPJLC103ROS4	12	2.5	70
YPJLC104ROS4	14	2.5	68
YPJLC105ROS4	12	3	69
YPJLC106ROS4	14	4	69
YPJLC107ROS4	11	4.1	70

Figure 2. Some data of the evaluation table to apply Multi-Attribute Utility Theory (MAUT) for product assessment by using D-Sight software.

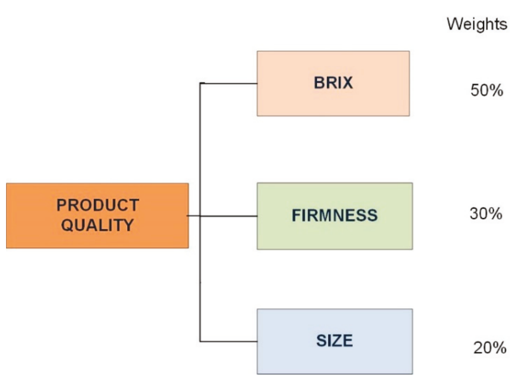


Figure 3. Criteria and weights to measure the quality of fruits: yellow peach.

Finally, it also necessary to establish the utility function for each criterion through the information provided by experts from the supermarket chain quality department. They provided direct assessment of partial value function for each criterion in several interviews. Using a global scale from zero to 100, the experts were questioned about assessing the value from the performance of products against each criterion [29]. Figure 4 shows the utility functions of criteria to evaluate the quality of fresh yellow peach. Brix degrees quantify sugars in the fruit and have great influence on its flavor. As shown in utility function (a), the company specifies a minimum value for this criterion, for which a greater value is ideal. When Brix degrees are very high, increases in their value provide fewer quality improvements than when the Brix degrees are lower.

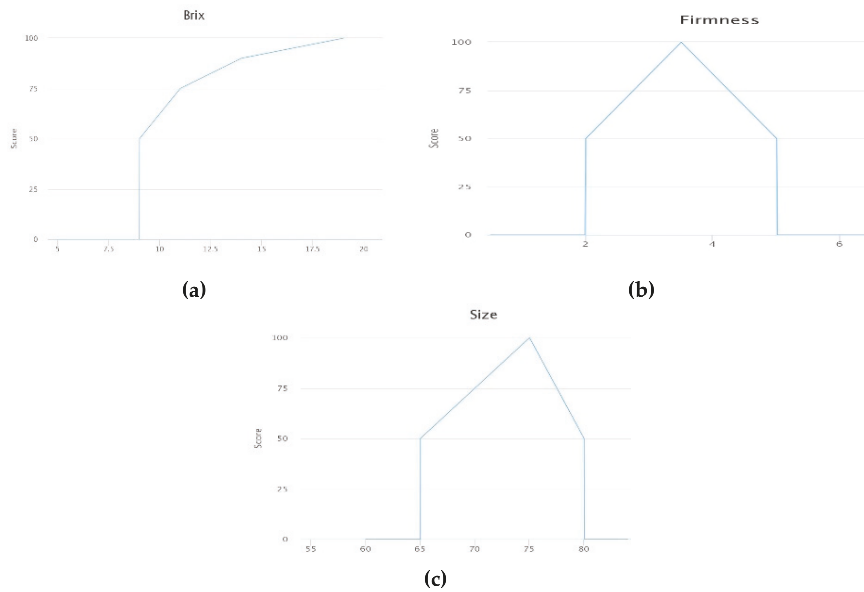


Figure 4. Utility functions of criteria for fresh fruit evaluation. (**a**) Brix degrees. (**b**) Firmness. (**c**) Size.

Figure 4b represents the utility function of firmness and (c) the utility function of size. In both cases, specifications set minimum and maximum values. Thus, values outside of this range have a score of zero. Inside this range, there are two sections. In the first one, the function increases until the most preferred value is reached. The utility function decreases more for greater criterion values.

Applying MAUT with all this real information, indicators for the quality of yellow peach are obtained. Figure 5 illustrates the results of the global score and the individual criterion contribution, represented by different colours. Brix degree is the most important criterion, as it has the highest weight (50%), followed by firmness (30%) and size (20%). The usefulness of these results is twofold. Firstly, they are useful at an operational level in the logistic platform, in order to reject those batches with the worst scores. Secondly, they are useful at a tactical/strategic level, when the company is evaluating and monitoring supplier performance.

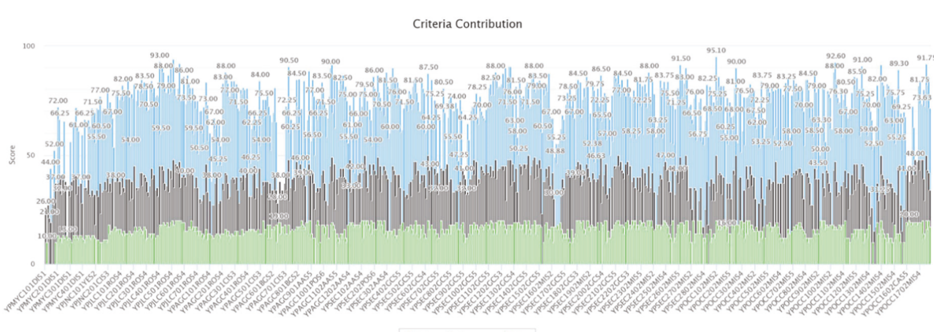


Figure 5. Quality indicators of yellow peach obtained by MAUT. All suppliers, 2018.

Figure 6 presents the same information as Figure 5 for only one supplier (S3). In this case, it is easier to note that in general the worst scores are for products that do not meet the specification for at least one criterion, whose value is below minimum or above maximum. As MAUT compensates for the performance of all criteria, an acceptable score is also feasible when some criteria have a very good performance, but one criterion does not satisfy the technical specifications. In this case, the company indicator would be zero.

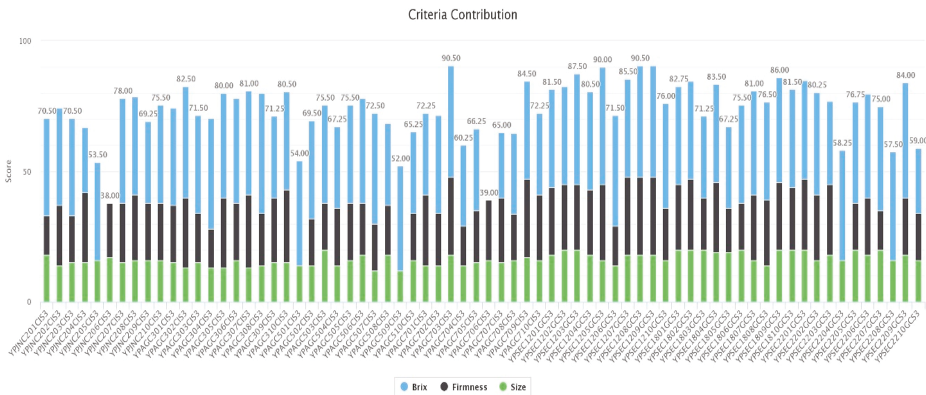


Figure 6. Quality indicators of yellow peach obtained by MAUT. Supplier 3, 2018.

The Global Visual Analysis is a very useful tool for the analyst, as it provides a different perspective on the results (Figure 7). The points represent products and the criteria are the green axes. Close points represent products with similar quality levels. Products with good performance with regard to a criterion are located in the direction of the axis of this criterion.

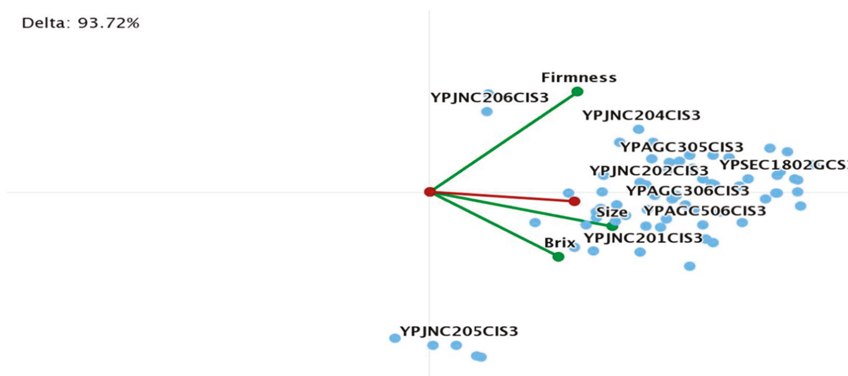


Figure 7. Global Visual Analysis of yellow peach obtained by MAUT. Supplier 3, 2018.

4. Results of Sustainable Supplier Evaluation: Comparing MAUT and PROMETHEE Approaches

4.1. Criteria for Sustainable Supplier Evaluation of Fresh Fruits

The performance of fresh food suppliers in supermarket chains depends on the quality of products provided by suppliers, in addition to other criteria needed to assess them from a sustainable perspective. In particular, the company assesses the fruit suppliers based on three main groups of criteria: logistic, commercial and "product quality". Logistic criteria are stockout, rejections (in logistic platform), and service capability. Commercial criteria include product innovation, conflict resolution, collaboration, and administrative functions. The "product quality" that a company evaluates is a subjective assessment of product quality made by a manager, followed by withdrawal when food safety problems occur. These criteria have some weaknesses; for example, they do not consider objective measures of the quality of products, but only consider the judgements/opinions of managers about the general performance of suppliers with respect to this issue. The manager evaluations for all criteria are measured on a scale from zero to 10. The company wants to improve its procedure to assess the food safety of suppliers and this paper provides new criteria for this purpose. In addition, another shortcoming of the company procedure consists of not including environmental criteria, with the exception of environmental certification or HACCP implementation as a prerequisite.

Sustainability requires taking into account economic, environmental, and social factors. Figure 8 presents a criteria hierarchy for sustainable supplier evaluation in fresh fruits that contributes significantly to both the literature and company management. To select the criteria, the authors have taken a literature review into account [26,42], as well as the results of a survey with managers of supermarket chains and interviews with experts. The survey included questions about the current system for evaluating fresh products and their suppliers and distinguished between criteria already applied and those that would be of interest to apply in the future. The criteria selection also considered the availability of reliable data in practice. The aggregated indicator of the quality of products provided by a supplier is the average of all product indicators from this supplier plus the standard deviation.

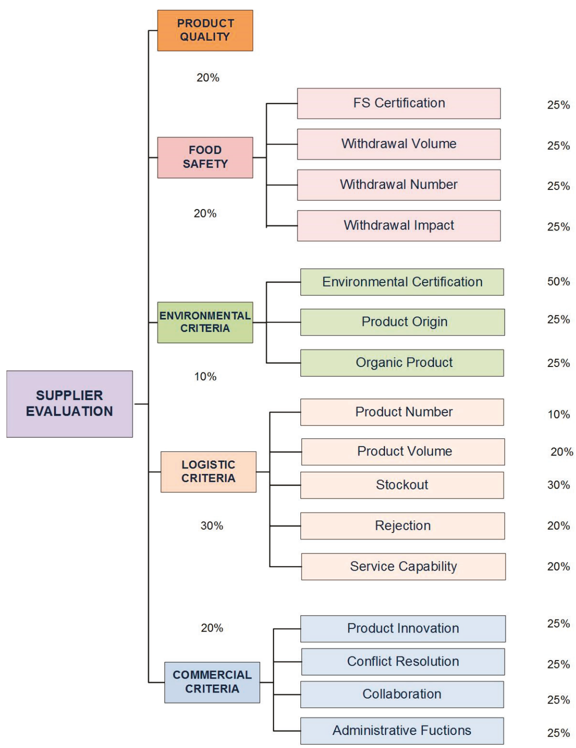


Figure 8. Hierarchy of criteria for sustainable supplier evaluation of fresh fruits. Weights of criteria are expressed in percentages.

Food safety is the most relevant criterion in food supply chain management. In general, food distribution companies qualify suppliers if they have food safety certifications. Nevertheless, from time to time crises arise due to food safety issues, which are difficult to manage by the companies affected and have great impacts from social and economic standpoints. Thus, the indicator of food safety from suppliers is measured through four sub criteria: food safety certification, withdrawal volume due to food safety issues, number of withdrawals, and withdrawals impact. If a supplier has at least one food safety certification, it receives the best value (100) in the evaluation table. When the supplier has HACCP implemented, the value is 50 and zero when it has neither of these options. HACCP implementation is necessary when the provider does not have any food safety certification. Withdrawal volume is expressed in percentage with respect to total quantity provided by the supplier. Finally, the following scale is used to assess the impact: none (100), low (75), medium (30), and high (0).

The model proposes as environmental criteria: environmental certification, product origin, and organic product. These criteria are qualitative, and are translated into numerical values for the multicriteria evaluation table as follows. If the supplier has environmental certification, the value assigned is 100 and is zero otherwise. The origin criterion distinguishes among local, national, or international sources (100, 75, 50). Organic products have better value than non-organic products, scoring 100 and 75, respectively.

The logistic criteria are the product number, product volume, stockout, rejection, and service capability. The number of varieties of yellow peach provided by a supplier is the number of products in this case study. All these data are quantitative and from databases of the company related to supplier performance in the logistic platform. Stockout and rejection criteria are measured in percentages over the quantity of product. The company monitors the degree of compliance with the day and time in order to measure the service capability of suppliers, which is the average of both percentages.

Finally, the commercial criteria group includes product innovation, conflict resolution, collaboration and administrative functions of suppliers. Managers of the company rate the supplier performance for these criteria using a scale from zero to ten.

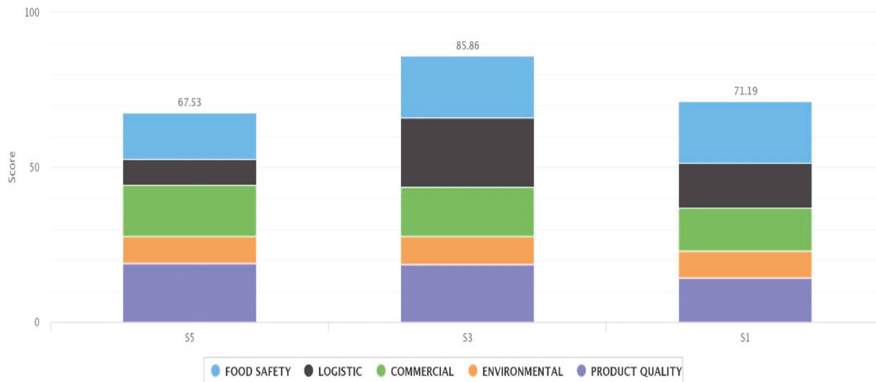
Following the flowchart in Figure 1, the second step is to carry out the supplier evaluation taking into account the scores (indicators) of all products provided by each supplier, as well as other relevant supplier criteria for the company. Figure 8 shows all criteria included in sustainable evaluation, as well as their weights, for applying MAUT and PROMETHEE.

4.2. Supplier Performance and Contribution of Criteria

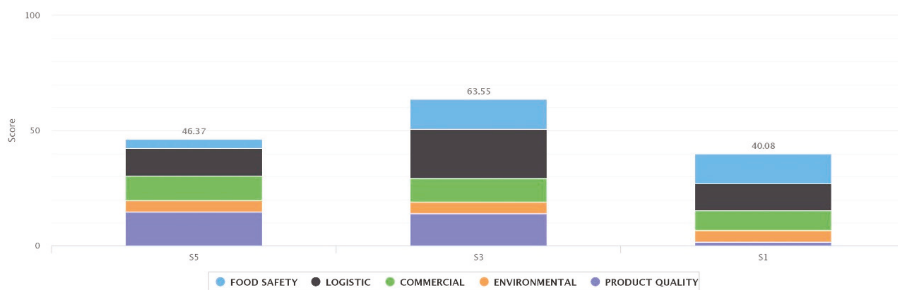
A company provided the data to complete the evaluation table with the performance of three suppliers, S1, S3, and S5, for all criteria, as well as information to build the utility functions to apply MAUT and the preference functions in PROMETHEE. This company assesses all the supplier performance criteria on a scale from zero to ten. In particular, the evaluation of the subjective quality from company is zero for S1, nine for S3, and eight for S5. The system proposed based on a MAUT methodology gives the following scores for the objective product quality with a scale from zero to 100: 64.16 for S1, 84.71 for S3, and 85.86 for S5.

This section presents the main results on supplier performance and the contribution of criteria to the global score of suppliers obtained by MAUT and PROMETHEE. It is necessary to highlight that the multicriteria approach to evaluate suppliers included the same four commercial criteria as the company used, with the same performance data. Nevertheless, the proposal presented considers ten new criteria: product quality, four criteria related to food safety, three environmental criteria, and two more logistic criteria in addition to stockout, rejection, and service capability. These new criteria allow the assessment of suppliers from a sustainability perspective.

Figure 9 shows the global indicators derived from multicriteria approach obtained by D-Sight software. The score value represents the supplier performance measured in a scale from zero to 100. MAUT has greater values than those obtained from PROMETHEE. The best supplier is the same in both multicriteria methods, S3 with a score of 85.86 from MAUT and 63.65 in PROMETHEE. Nevertheless, the ranking is different, as S1 is the second and S5 is the third in MAUT, while the order is S5 and S1 in PROMETHEE. The company attributes the following scores to these suppliers in a scale from zero to ten with the criteria indicated previously: 8.58 for S3, 5.70 for S1, and 5.30 for S5. Thus, supplier S3 is the best supplier according to company procedure and both multicriteria approaches, mainly because of the good logistic performance and the weight of this criterion (40% in a company system and 30% in a multicriteria approach). Although the company assigns a very good score to the subjective product quality of S5 and the worst to S1, the global score of S1 is better than S5.



(**a**)



(**b**)

Figure 9. Global indicators of suppliers: (**a**) MAUT (**b**) Preference Ranking Organisation Method for Enrichment Evaluation (PROMETHEE).

Figure 9 also shows the relative contribution of each group of criteria to the global score of suppliers that present important differences. This is mainly noticeable in food safety and product quality. The compensatory nature of MAUT, in which bad performance in one criterion can be compensated for by good scores in other criteria, explains these results. In contrast, PROMETHEE, a non-compensatory method, is based on pairwise comparisons of suppliers.

Figure 9 also highlights the greater discriminant power of the PROMETHEE method, especially for food safety and product quality. Figure 10 shows the profiles of suppliers using a different graph, which illustrate how S3 dominates other suppliers in almost all criteria. Figures 9–11 offer results from multicriteria analysis, which are easy to understand for managers and facilitate decision making.

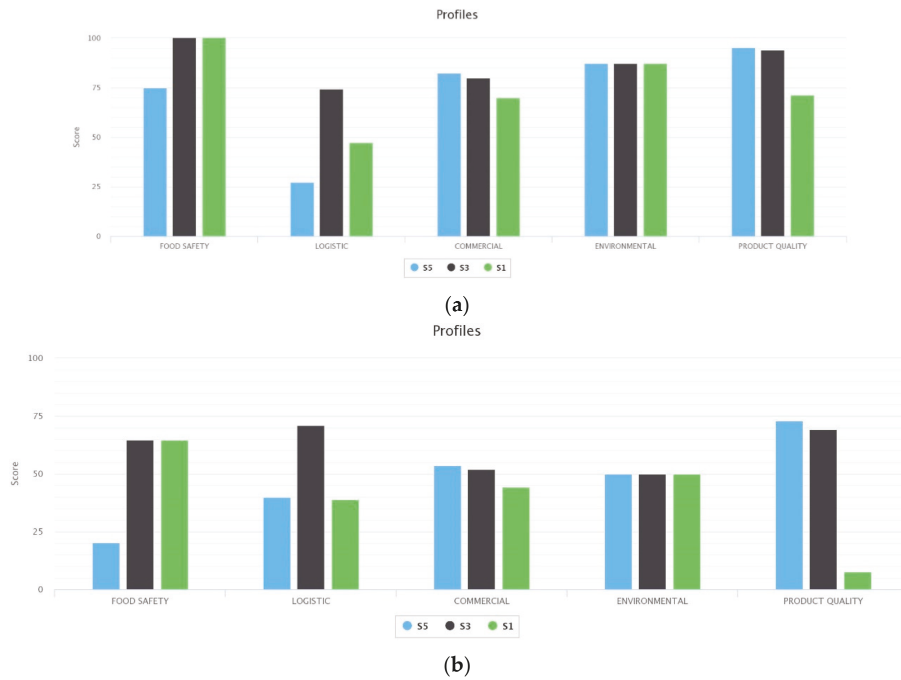


Figure 10. Performance of suppliers by a group of criteria. (**a**) MAUT. (**b**) PROMETHEE.

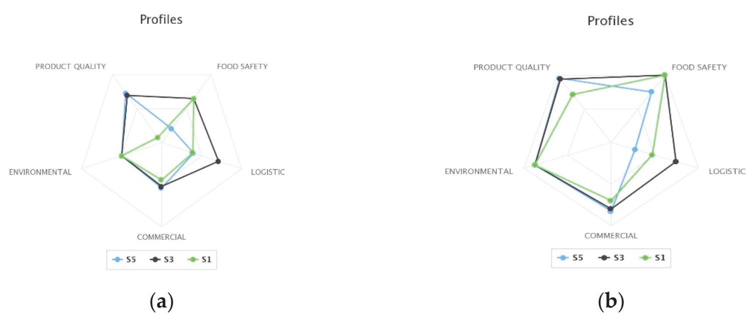
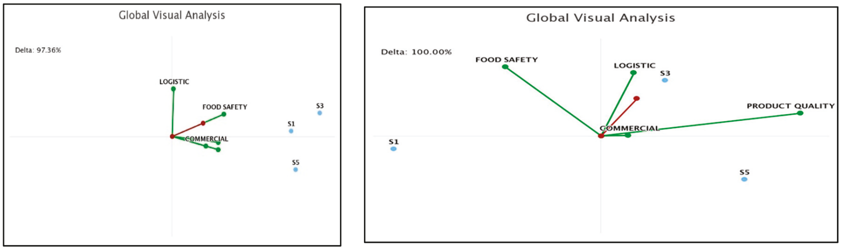


Figure 11. Spider web graph of supplier profiles. (**a**) MAUT (**b**) PROMETHEE.

4.3. Capabilities for Supplier Segmentation of MAUT and PROMETHEE

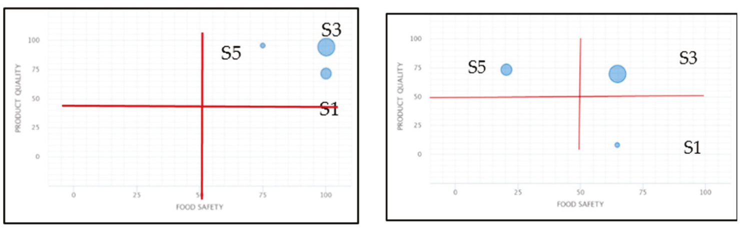
D-Sight software [43], used to apply MAUT and PROMETHEE in this research, provides an interesting representation of results, named Global Visual Analysis, which corresponds to the GAIA plane developed for the PROMETHEE method by Brans and Mareschal [31]. In Figure 12b green axes represent the main groups of criteria and the red stick indicates the best alternative. The longer the axis, the more discriminant the criterion. S3 is the best supplier and it is especially good for logistics, as its point is located in the direction of the logistic axis. In addition, this representation highlights that S1 has a bad performance in product quality, as it appears in the opposite direction to the criterion axis. For the same reason, S5 shows weaknesses in food safety. This information is shown clearly in the graph from PROMETHEE results, but this is not clear in the graph from MAUT (Figure 12a).



(**a**) (**b**)

Figure 12. Global Visual Analysis of suppliers. (**a**) MAUT (**b**) PROMETHEE.

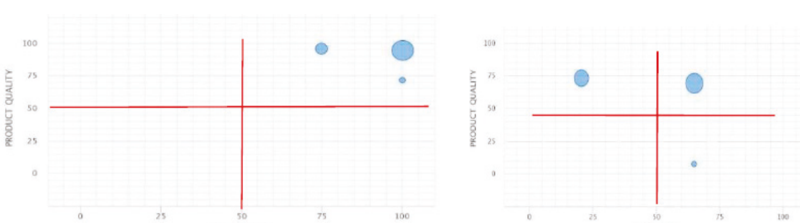
Global Visual Analysis of suppliers is very useful for analysts, but is more difficult to understand for managers. In practice, bubble graphs such as those in Figure 13 are more useful for individual and collaborative decision making in companies interested in developing the best relationship with suppliers, as recommended by the latest trends in supply chain management.



(**a**) (**b**)

Figure 13. Supplier segmentation by food safety and product quality. Scenario 1. (**a**) MAUT (**b**) PROMETHEE.

Figure 13 represents the suppliers according to food safety and product quality scores. The global score of suppliers is taken into account in the size of the bubble. Comparing results from MAUT and PROMETHEE, the ranking is different, as explained in Section 4.2. This figure highlights the higher discriminant power of PROMETHEE, which allows for segmentation of suppliers based on groups of criteria and is becoming a very important practical tool for decision making in companies. To analyze the sensitivity of the scores to changes in criteria weights, Figure 14 shows the results for another scenario, scenario 2, in which the weight of product quality has been increased to 40%, while the weights of logistics and commercial criteria are 20% and 10%, respectively. These changes do not modify the segmentation of suppliers.



(**a**) (**b**)

Figure 14. Supplier segmentation by food safety and product quality. Scenario 2. (**a**) MAUT. (**b**) PROMETHEE.

5. Discussion

Product qualifying and supplier evaluation are critical supply chain management issues in food distribution companies, mainly due to food safety incidents that can cause negative effects on consumer health, sales, and brand image, among others. Environmental criteria are also increasingly important for consumers and economic criteria are relevant in order to provide profits for companies and affordable food to society. If a product is good enough for the consumer, this is related to its own performance on criteria selected to qualify the product. Thus, the MAUT method provides an appropriate approach to carry out food product evaluation. In addition, it is easy to use and apply at an operational level in companies, as shown in Section 3.

Evaluating suppliers from a sustainable perspective can be done by both MAUT and PROMETHEE. The main advantages and drawbacks of these approaches derive from the compensatory nature of MAUT and the non-compensatory character of PROMETHEE, based on pairwise comparisons of the supplier performance with respect to all criteria. Section 4 has shown the better suitability of the latter to identify strengths and weaknesses of each supplier. Similar results were obtained in the decision support system related to supplier segmentation validated in a manufacturing company, which makes intermediate products for other companies of food, pharmaceuticals, and chemicals sectors [23]. In this case, the evaluation was focused on chemical and packaging goods, the products and supplier criteria were grouped into critical and strategic criteria, and sustainability was not the main issue studied. Therefore, the criteria considered were quite different to those proposed in this research for fresh fruits in supermarket chains.

The proposal by Lau et al. for fresh food included three multicriteria techniques [26]. Fuzzy AHP to determine the weights of criteria, while we propose AHP or consensus among managers from all departments involved. These authors first applied the non-compensatory ELECTRE method to qualify suppliers from the food safety perspective, followed by TOPSIS to evaluate only the suppliers that verified safety specifications. TOPSIS is a classical multicriteria method with good theoretical properties that provides quantitative indicators based on the distance of the alternatives with respect to the ideal point. Nevertheless, the current trends in supply chain management encourage evaluating and monitoring suppliers systematically, ensuring that they satisfy legal regulations and technical specifications, in order to develop the most appropriate relations with suppliers according to company strategy and preferences [3,23,31].

Regarding the specific measures to evaluate fresh food suppliers, Lau et al. included 10 main criteria: product, quality, food safety, price, delivery, serviceability, commercial position, supplier relationship, risk factor, and Corporate Social Responsibility (CSR). Each main criterion includes between five and nine sub criteria, with more than 60 in total. The qualitative or quantitative nature of many of them is unclear, as is whether the data are sourced from manager evaluations or from quantitative values of databases. The weights of the main criteria vary from 4% for CSR to 16.5% for quality and food safety, which includes certifications, audits, and traceability. Our proposal includes food safety certifications and HACCP qualifications, as well as three new criteria which are the withdrawal volume, number, and impact of withdrawals.

There are some remarkable differences between the approach of Lau et al. [26] and the system proposed in this research. The perspective of our evaluation is global sustainability, while Lau et al. do not consider environmental criteria specifically. These authors only include eco-labeling as a sub criterion in the CSR criterion with very little weight. They also include supplier relationship as a main criterion, whereas this is something to be monitored and reported on from the results of supplier segmentation in our proposal. For example, the supplier is one with a long-term contract, it is advisable to maintain this relationship, or the company should set out new measures if poor performance is found in the period evaluated.

The selection and number of criteria, a clear definition and how to measure their performance, are key issues in the real implementation of a decision support system based on MCDM. In particular, the multicriteria model should be completed. This means that it includes all relevant criteria according to the company's strategic objectives. At the same time, the selected criteria should have reliable and available data to measure their performance. Many of the case studies on supplier evaluation are mainly based on the manager's assessment. Our proposal is to balance criteria number and model completeness together with data quality and availability. Sustainable supply chain trends in the food sector, such as traceability, facilitate the collection of data needed to implement decision support systems to evaluate and monitor products and suppliers.

The system proposed, based on both MAUT and PROMETHEE, is easy to understand and implement as the core of a decision support system useful for product and supplier assessment in food distribution companies. MAUT is appropriate to qualify fresh food, but has less power to rank and classify suppliers than PROMETHEE. The power of outranking methods, such as PROMETHEE and ELECTRE, comes from their focus on pairwise comparison of alternatives. Nevertheless, ELECTRE is more complex and difficult to understand and apply, as more inputs and parameters are required. On the one hand, MAUT does not have the same rank reversal problems as TOPSIS, which only needs the weights of criteria and is based on an easy algorithm, but it is not appropriate for sustainable supplier evaluation. On the other hand, PROMETHEE has demonstrated the power of graphical tools to carry out more in-depth studies with Global Visual Analysis (GAIA plane), as well as its graphical capabilities to detect strengths and weaknesses of the suppliers' performance and design supplier segmentation to inform strategic decision making.

Finally, it is necessary to highlight that LCA is a common approach in the literature dealing with product sustainability. Nevertheless, LCA is not as appropriate a tool to qualify, evaluate, and monitor food products and their suppliers as the MCDM methods are, as MCDM methods facilitate decision making in companies at the operational, tactical, and strategic level [1].

6. Conclusions

Qualifying and evaluating suppliers are two common and relevant supply chain management tasks in large companies. There is a huge number of articles on this topic, but they are focused on selecting providers for one product only in manufacturing industries. Nevertheless, companies work in more complex and changing contexts, where selecting a small number of suppliers per product is the trend in supply chain management. In addition, there is a lack of literature on supplier evaluation in food distribution companies, which have an increasing global impact from an economic, environmental, and social point of view.

This article proposes a system based on two multicriteria methods in order to first qualify food and then evaluate its quality, whose results are used in a second step, along with other criteria from providers, focused on sustainability evaluation of fresh food suppliers. The system combines a compensatory multicriteria technique, MAUT, which is easy to use and appropriate to qualify and obtain a quality indicator for products, with PROMETHEE, a non-compensatory method. The models proposed have been validated for fresh food in a supermarket chain, mainly using historical data on fruits rather than opinions, judgements and/or direct ratings from managers. This research represents the first time that both approaches, suitable for supplier evaluation, are applied to this purpose in distribution companies. The system includes economic, environmental, and social criteria to develop sustainability indicators for suppliers, which allow them to improve food safety, one of the most relevant social criteria.

Global and partial indicators from suppliers provide information on the most appropriate decisions and relations between distribution companies and their providers. An example of this is whether to accept or reject a fresh food batch when it is checked at the logistical platform, as well as evaluating the quality of fresh food. Poor performance in food safety can lead to some suppliers being disqualified. As MAUT is easy to apply and interpret, it can be used successfully in real implementations at an operational level in logistic platforms. MAUT is also easy to apply and is useful for monitoring global performance of suppliers in a season, which can be carried out by PROMETHEE. In addition, this latter method is more suitable for supplier segmentation and provides additional information to analyze their performance in depth, as it discriminates more among supplier strengths and weaknesses.

Finally, in future research it would be interesting to extend this proposal to a large number of fruits and vegetables, including organic products in the evaluation. Likewise, developing appropriate criteria and models to evaluate the food safety and sustainability of fresh meat and its suppliers could contribute significantly to improving not only food distribution supply chain management, but also providing benefits for companies and people. To achieve this end, multicriteria models must be based on transparent and objective data for clearly defined criteria.

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Author Contributions: All author designed the model and interpreted the data and results of the models. M.S. and C.M. carried out literature review, multicriteria analysis, model validation and wrote the manuscript.

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Building a Composite Indicator to Measure Environmental Sustainability Using Alternative Weighting Methods

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Abstract: Environmental sustainability in agriculture can be measured through the construction of composite indicators. However, this is a challenging task because these indexes are heavily dependent on how the individual base indicators are weighted. The main aim of this paper is to contribute to the existing literature regarding the robustness of subjective (based on experts' opinions) weighting methods when constructing a composite indicator for measuring environmental sustainability at the farm level. In particular, the study analyzes two multi-criteria techniques, the analytic hierarchy process and the recently developed best-worst method, as well as the more straightforward point allocation method. These alternative methods have been implemented to empirically assess the environmental performance of irrigated olive farms in Spain. Data for this case study were collected from a panel of 22 experts and a survey of 99 farms. The results obtained suggest that there are no statistically significant differences in the weights of the individual base indicators derived from the three weighting methods considered. Moreover, the ranking of the sampled farms, in terms of their level of environmental sustainability measured through the composite indicators proposed, is not dependent on the use of the different weighting methods. Thus, the results support the robustness of the three weighting methods considered.

Keywords: agricultural sustainability; environmental performance; sustainability indices; multi-criteria analysis; analytic hierarchy process; best-worst method; irrigated olive groves; Spain

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1. Introduction

There is a broad consensus about the definition of 'sustainable agriculture' as an activity that satisfies the following requirements for an indefinite period of time [1,2]: a) it protects biodiversity and natural resources and prevents environmental degradation, b) it is economically viable, and c) it is socially acceptable. Taking these requirements into consideration, agricultural sustainability can be defined as a concept that encompasses three main dimensions:

- *Environmental sustainability*. Sustainable agriculture must preserve biological biodiversity and the provision of ecosystem services. Thus, environmental sustainability can be defined as the ability to ensure greater agricultural productivity while simultaneously conserving natural resources and preventing the degradation of ecosystems.
- *Economic sustainability*. Sustainable agriculture must be economically viable, ensuring not only adequate profitability for farmers (the microeconomic level) but also a positive contribution to national/regional income (the macroeconomic level).

- *Socio-cultural sustainability*. Sustainable agriculture must be socially and culturally beneficial, i.e., it should ensure food security and the fair and equitable distribution of the wealth it generates, as well as contribute to the viability of rural communities.

This paper is focused on the measurement of environmental sustainability. To date, various indicator-based methods have been developed for this purpose, constructed using a wide range of agri-environmental indicators (AEIs) (for a review of the approaches proposed, interested readers can consult Bockstaller et al. [3]). All these proposals are based on large sets of AEIs aimed at assessing the multidimensional environmental impacts of agricultural activity and the provision of ecosystem services (natural resources, biological processes, biodiversity, etc.) (e.g., [4–6]). However, the quantification of environmental sustainability through AEIs has been criticized for several reasons. On the one hand, there are technical problems related to data and measurability (qualitative aspects that are hard to quantify) issues and a lack of sound ecological models that enable the interpretation of the indicators (e.g., a lack of reference levels or thresholds for reversibility processes), the multiple spatial scales needed for an overall assessment or the appropriate time horizon required (extended monitoring is needed for long-term environmental changes) [7,8]. On the other hand, there are also operational concerns related to the interpretation of the whole set of indicators required for such analyses, which is an obstacle to their use as a practical decision-support tool. In order to deal with the latter problem, composite indicators or indexes have been proposed as a means of summarizing the information provided by multiple indicators into an overall assessment of environmental performance (see, for instance, [9,10]).

In order to construct a composite environmental indicator, specific methodological approaches for the normalization, weighting, and aggregation of base AEIs must be selected from several alternatives (see further details in Section 3). All these choices have a significant effect on the overall composite indicator built. The inherent subjectivity of the choice of these approaches is behind most of the criticisms leveled at the different sustainability indexes proposed in the empirical studies carried out to date [11]. This issue has prompted an academic debate on the robustness and sensitivity of the methodological approaches used in the construction of composite indicators [12,13].

The objective of this paper is to contribute to the existing literature regarding the robustness of three alternative weighting methods [14]. For this purpose, we build a composite environmental indicator using three different methods to assess the relative importance of the individual base AEIs; then, by comparing the results obtained from a real-world case study, we provide further insights into the robustness of the weighting methods implemented.

In this context, it is worth mentioning that two of the weighting methods used in this paper are at the core of the multi-criteria decision-making (MCDM) paradigm, since they are used as key tools to provide information about the relative importance of the different criteria considered in these kinds of problems. For this reason, MCDM weighting procedures have commonly been used to build composite indicators [15], with the analytic hierarchy process (AHP) being the most popular one (e.g., [16–18]). Moreover, other more consistent and less time-consuming weighting methods have recently been developed, with the notable among them being the best-worst method (BWM) [19]. As this is a new technique, there have only been a few applications to date, and it has not yet been used in the construction of composite indicators. In this paper, we use the two aforementioned multi-criteria methods, in addition to the more straightforward point allocation (PA) method, to weight the base AEIs that are to be included in an index. We then compare the results obtained from the three methods in an empirical case study. To the best of our knowledge, this is the first study focused on the analysis of the robustness of weighting methods when constructing a composite environmental indicator, although there have been several empirical studies comparing some alternative weighting methods in different types of composite indicators (e.g., [20,21]). The comparative analysis proposed will enable us to draw useful conclusions about the construction of sound composite indicators.

The empirical case study considered is the assessment of the environmental sustainability of olive groves in Spain. For this purpose, the composite environmental indicator built (ENV_SUST) relies on previous research focused on the selection of relevant AEIs for this particular agricultural system [22], and uses primary data gathered from Spanish olive farms to calculate the whole set of selected AEIs at the farm level [23]. In any case, it is worth noting that, as far as the authors are aware, this paper is the first to develop a single composite environmental index for an overall assessment of environmental performance in olive growing. Thus, this paper also contributes to the existing literature by providing a sound instrument that is particularly useful for designing targeted policy interventions aimed at promoting sustainable olive farming.

2. Olive Farming in Spain: Environmental Sustainability Assessment

2.1. Recent Developments of Olive Groves in Spain

The current area of olive groves in Spain has reached its historically highest level, with around 2.5 million hectares (14% of the country's utilized agricultural area). In fact, Spain is the world's leading olive-producing country, accounting for one-third of the total olive grove area worldwide and half of the total olive oil production.

Spain's accession to the EU in 1986 allowed the Spanish olive sector to benefit from the implementation of the Common Agricultural Policy (CAP), which granted olive growers coupled subsidies that made olive farming more profitable than other types of agriculture (i.e., extensive herbaceous crops). The CAP subsidies encouraged these farmers to increase their olive grove area and olive production. This process of expansion has been also supported by new growing techniques aimed at production intensification, such as irrigation (olive has traditionally been a non-irrigated crop) and higher tree density (increasing from traditional densities of around 100 olive trees per hectare to 300–500 trees per hectare in 'intensive' orchards, or even more than 1000 trees per hectare in 'super-intensive' ones). As a result of these changes, Spain has increased its olive grove area by 25% between 1990 and 2020, and doubled its production of olive oil.

However, this expansion and intensification of Spanish olive groves has given rise to a number of environmental problems [23,24]:

1. *Soil erosion*. Erosion is the main environmental problem caused by this crop. The high soil erosion rates are due to the fact that more than 40% of all olive groves are located on land with unfavorable soil conditions for agricultural production (steep slopes, land particularly sensitive to erosion, or affected by frequent torrential rain), and that poor soil management by farmers has damaged natural vegetation cover (leading to farms with uncovered soils) [25]. This environmental impact has been aggravated in recent years by the expansion of olive groves into areas with especially adverse characteristics (steep slopes, extreme torrential rainfall, high erodibility of soils) [26].
2. *Loss of biodiversity*. One of the main characteristics of olive groves in the 1980s (under traditional farming) was the high biodiversity associated with the crop, with olive being an example of a 'high natural value' agricultural system. The low-intensity olive farming (minimum use of agrochemicals) and the existence of old olive trees with semi-natural herbaceous vegetation located in areas with different land uses (vineyards, cereals, pastures, and Mediterranean forest) provided a varied habitat, where a large number of insects, birds, reptiles, and mammals found refuge. However, the extension (large olive monoculture areas where hedgerows, stone walls, and islands of shrubs and trees have been eliminated) and intensification of olive groves (disappearance of vegetable cover, intensive use of biocides, fertilizers and machinery, water pollution, and soil erosion) has changed this situation, leading to a reduction in both the number and diversity of animal species in olive grove systems [27,28].
3. *Non-point source water pollution*. Modern olive growing has contributed to a decline in water quality due to the intense use of agrochemical products (mainly herbicides and fertilizers). This has resulted in non-point source water pollution problems in rivers, reservoirs and aquifers. Although in recent years some of the most polluting products widely used in olive farming (e.g., simazine

and diuron) have been banned, water quality could be further improved by modifying some of the current olive farming practices [29].

4. *Overexploitation of water resources*. Before the 1990s, most olive trees in Spain were rain-fed, but the intensification of the crop has seen the emergence of 800,000 hectares of irrigated olive groves. Although olive trees have low water requirements and are usually irrigated using highly efficient irrigation systems (water consumption using drip irrigation is around 1500 m^3/ha·year), there is substantial pressure on water resources [30]. Increasing water extraction not only causes the overexploitation of water resources but also jeopardizes the ability to meet other water demands in basins with a higher degree of water scarcity [31].

It is worth noting that several policy initiatives have been implemented in recent years to (partially) solve all these relevant environmental problems related to olive groves, by encouraging farmers to adopt various biodiversity-friendly and resource conservation practices. Along with the rational use of agrochemicals and water, these include some compatible soil conservation practices, such as disposing of olive-desuckering debris without burning, which helps mitigate climate change; the shredding of olive-pruning debris for use as soil cover, improving soil texture and reducing the impact of rain and water run-offs; and the use of cover crops under mower control as a sustainable practice in terms of soil protection [26,32,33]. In addition, some practices related to functional elements (hedgerows, riparian vegetation, plots margins, etc.) have proven effective in enhancing biodiversity as well as having a positive effect on other ecosystem services, such as landscape aesthetics [34]. Yet there is still plenty of room for further improvement. To effectively guide the future development of olive groves, more in-depth analyses are required, especially those that provide a quantitative assessment of the environmental performance of individual olive farms.

2.2. Indicators Measuring Environmental Sustainability of Olive Farming

Although there are several methodological frameworks for the quantitative assessment of the environmental sustainability of agricultural systems, there is widespread scientific agreement that constructing and calculating environmental indicators is the most suitable approach for this purpose [35,36]. Thus, the present study relies on the set of AEIs proposed by Gómez-Limón and Riesgo [22] to evaluate the sustainability of olive farms in Spain.

In order to evaluate the environmental sustainability of agriculture, the approach followed is founded on the SAFE (*Sustainability Assessment of Farming and the Environment*) analytical framework [37]. SAFE is based on a hierarchical structure with three levels: i) principles, ii) criteria and iii) indicators. *Principles* are general conditions for achieving environmental sustainability related to the ecological functions of the agro-ecosystems. In this sense, the environmental sustainability of agricultural systems centers on two principles regarding the protection of (a) biodiversity and (b) natural resources. *Criteria* are the resulting states of agricultural systems when their related principles are respected. For the particular case of olive groves, biodiversity is considered to be protected when the following elements are guaranteed: a1) olive grove genetic diversity (trees in the orchard), a2) biological diversity (a range of different species within the farm boundaries, from 0.1 km^2 to 10 km^2), and a3) habitat diversity (a range of different habitats within the landscape unit, from 10 km^2 to 1000 km^2). In addition, natural resources conservation is achieved when: b1) soil erosion is minimized, b2) soil fertility is protected or enhanced, b3) soil and water quality are maintained or improved, b4) water extraction is minimized, and b5) the energy balance (primary energy supply minus primary energy used per cultivation unit) is optimized. Lastly, *indicators* are variables that can be assessed to measure compliance with a criterion, thus producing a representative picture of the environmental sustainability of the agricultural system under analysis. Taking the former criteria into account, a set of 11 AEIs was selected on the basis of analytical soundness, measurability and policy relevance [38,39], as shown in Table 1. Technical details on why each indicator was chosen, how it was calculated at farm level and how its value should be interpreted can be found in Gómez-Limón and Arriaza [23].

Table 1. Principles, criteria and indicators of the environmental sustainability of olive groves.

Principles	Criteria	Agri-environmental Indicators (*ACRONYM*) [Measurement Unit]
Biodiversity protection	Ensuring olive grove genetic diversity	Number of olive grove varieties (*NUMVAR*) [olive grove varieties number]
	Enhancing or protecting biological diversity	Index of biological diversity (*DIVERSIND*) [dimensionless] bounded [0,1]
		Pesticide risk (*PESTRISK*) [kg live organism/ha·year]
	Enhancing or protecting habitat diversity (ecosystem)	Percentage of land with other crops (*OTHERCROP*) [%]
		Percentage of non-cultivated land (*NONCULTIV*) [%]
Natural resources conservation (soil and water)	Minimizing soil erosion	Soil erosion (*EROSION*) [t/ha·year]
	Enhancing or protecting soil fertility	Soil organic matter (*ORGMAT*) [dimensionless] bounded [0,1]
	Enhancing or protecting soil and water quality	Nitrogen balance (*NITROGBAL*) [N kg/ha·year]
		Residual herbicide use (*RESHERB*) [kg active matter/ha·year]
	Minimizing water extraction	Irrigation water use (*WATERUSE*) [m^3/ha·year]
	Optimizing energy balance	Energy balance (*ENERGYBAL*) [MJ/ha·year]

Source: Gómez-Limón and Riesgo [22] and Gómez-Limón and Arriaza [23].

3. Building a Composite Indicator to Measure Environmental Sustainability

3.1. The Methodological Approach for Building Composite Indicators

The literature contains a plethora of techniques for building environmental sustainability indices. In any case, the Organization for Economic Co-operation and Development (OECD) and the Joint Research Centre of the European Commission (JRC) [11] provide guidance on the transparent construction of composite indicators, identifying the steps that analysts should follow:

1. *Indicator selection and data gathering*. As explained in Section 2, an essential element of this kind of study is the selection of relevant AEIs based on strict quality criteria, and accurate data gathering to calculate the empirical values of these indicators. Given the huge number of possible indicators, the use of a solid theoretical framework is recommended; in this paper, the SAFE approach is applied.
2. *Normalization of indicators*. Transforming indicators into dimensionless variables (normalization) is essential before they are weighted and aggregated, as they have usually been calculated using different units of measurement. To be able to compare them and perform arithmetic operations on them, they need to be expressed in homogeneous units within the same range. In our case, selecting from among the various normalization techniques available [40,41], we applied the min-max or re-scaling normalization, taking the reference values for each of the AEI considered as sustainability thresholds. Thus, the values of all the normalized indicators vary within a dimensionless range [0,1], where 0 is assigned to all cases where the AEI value is worse than or equal to an 'unacceptable level of sustainability' (i.e., the worst environmental performance)

and 1 is assigned to all cases where the AEI value is better than or equal to a 'desired level of sustainability' (i.e., the best environmental performance).

3. Weighting of indicators. Assigning weights enables us to identify the relative importance of the individual indicators. There are several valid procedures for weighting indicators, but the composite indicator may yield different results depending on the procedure used [42,43]. Therefore, the selection of a particular technique is a challenging task. The weighting techniques for constructing indices can be divided into 'objective' and 'subjective' ones [44]. With the former, weights are derived endogenously using statistical or mathematical procedures, such as principal components analysis (PCA), data envelopment analysis (DEA), the benefit of the doubt (BOD) approach or regression analysis (RA). With the latter, weights are determined exogenously on the basis of value judgments expressed by experts or decision-makers, as is the case with AHP, BWM, PA, budget allocation process (BAP) or conjoint analysis (CA). It is worth mentioning that environmental sustainability is a technical concept that requires scientific knowledge to define and measure, especially when it is applied to a specific ecosystem (in this case, olive groves in Spain). This justifies the use of exogenously determined weights in our case study, based on the opinion of experts on the environmental performance of olive groves. In particular, we have chosen AHP because it is the most commonly-applied technique among the subjective weighting methods available, BWM has been selected due to its novelty and the presumed advantages over AHP, and PA because it is an explicit and straightforward weighting method.
4. *Aggregation of indicators*. The OECD and JRC [11] suggest several alternative functional forms that allow indicators to be aggregated, explaining their pros and cons. Depending on the aggregation method used to develop the indices, the results and the conclusions drawn from them may differ from case to case. Thus, the choice of the aggregation method is also subject to criticism relating to the shortcomings of the technique used [40,43,45]. The key issue when selecting a functional method of aggregating indicators is the compensability or marginal rate of substitution among indicators [18]: a) additive linear functions implicitly assume total compensability among indicators, b) multiplicative and geometric functions permit partial compensability, and c) non-compensatory functions assure non-compensability. In order to minimize the subjectivity regarding the method employed to build the composite indicator measuring environmental sustainability, the multicriteria function based on the distance to the ideal point measured by different metrics (i.e., different degrees of compensability) and developed by Díaz-Balteiro and Romero [46] has been chosen for implementation.

Having made the decisions explained above, the composite indicator measuring the environmental sustainability of olive farms (ENV_SUST) can be calculated as a function of the normalized values of the 11 AEIs taken into account (I_k), the weights assigned to each of these indicators (w_k) and the compensation parameter (λ), following the expression:

$$ENV\_SUST = (1-\lambda)\cdot\left[\underset{k}{Min}(w_k \cdot I_k)\right] + \lambda \cdot \sum_{k=1}^{k=11} w_k I_k. \quad (1)$$

The parameter λ ranges between 0 and 1, thus affecting the degree of compensability among the indicators. Here we consider five values of the compensation parameter ($\lambda = 0$, $\lambda = 0.25$, $\lambda = 0.5$, $\lambda = 0.75$ and $\lambda = 1$), which gives us the three abovementioned possibilities: (a) total compensability ($\lambda = 1$), (b) various degrees of partial compensability ($0 < \lambda < 1$) and (c) zero compensability ($\lambda = 0$).

3.2. Alternative Techniques for Weighting Indicators

As has been previously stated, this paper is focused on the role of weighting techniques when constructing composite indicators, in order to provide further empirical insights about their robustness. For this reason, in this paper we use three exogeneous weighting methods (i.e., based on expert opinion) to determine the priorities (global weights) (w_k) of the whole set of AEIs used to construct the *ENV_SUST* index: AHP, BWM, and PA.

The AHP was initially developed as a decision-support tool for making complex decisions [47], but it was subsequently adapted to index construction; this technique is also particularly useful for weighting sustainability attributes when constructing composite indicators [13,48]. The implementation of this method involves the following steps: first, the weighting problem is structured as a tree-based hierarchy, where the overall goal of the problem (in our paper, the environmental sustainability of irrigated olive grove) is at the top of the hierarchy. Decision criteria contributing to the main goal are placed at an intermediate level (i.e., biodiversity protection and conservation of natural resources in our case) and decision subcriteria are positioned at the lowest level (the base AEIs in our case). Second, experts individually perform pairwise comparisons at each node of the hierarchy, expressing their preferences as to how much one (sub)criterion should be valued over another, following Saaty's fundamental scale (from 1 −equal importance− to 9 −extreme importance of one (sub)criterion over another). Based on these expert judgments, reciprocal square matrices can be built for each node. Third, the local weights of the sets of criteria (biodiversity protection and conservation of natural resources) and subcriteria (the base AEIs) are calculated using the main eigenvector method proposed by Saaty [49]: $AW = \lambda_{max}W$, where λ_{max} is the maximum eigenvalue of A and W is the vector of local weights. AHP allows some degree of inconsistency in the decision maker's judgments, measured using a consistency ratio that must not exceed predefined values [50]. Fourth, global weights (w_k) of the base AEIs are calculated by multiplying the local weight of each subcriterion (AEI) by the priority of its parent node (its related principle).

The BWM is a novel multi-criteria decision-making technique [19]. Like AHP, this method is suitable for weighting attributes, and although it has only recently been developed, it has already been applied to the construction of composite indicators [51,52]. BWM requires fewer pairwise comparisons than AHP (in the AHP method, the number of comparisons is n (n − 1)/2, while for the BWM, the number of comparisons is 2n − 3), which may lead to more consistent and reliable results. In order to derive the global weights of the base AEIs, BWM entails the following steps: first, as in AHP, the problem is structured as a tree-based hierarchy (overall goal, decision criteria, and decision subcriteria). Second, the best (sub)criterion (i.e., the most important) and the worst (sub)criterion (i.e., the least important) of the set of (sub)criteria are identified by the expert. Third, the preference for the best (sub)criterion over all the other (sub)criteria is determined using a number between 1 and 9, similar to Saaty's fundamental scale. The expert's preferences are then used to generate the Best-to-Others vector: $A_B = (a_{B1}, \ldots, a_{Bk}, \ldots, a_{BK})$, where a_{Bk} shows the preference for the best (sub)criterion B over (sub)criterion k, and $a_{BB} = 1$. Fourth, the preferences of all the (sub)criteria over the worst (sub)criterion are determined using a number between 1 and 9, as in the previous step. This information enables the construction of the Others-to-Worst vector: $A_W = (a_{1W}, \ldots, a_{kW}, \ldots, a_{KW})^T$, where a_{kW} shows the preference for the (sub)criterion k over the worst (sub)criterion W, and $a_{WW} = 1$. Finally, the local weights of decision (sub)criteria and the corresponding indicator of the consistency of responses (ξ^L) are obtained by solving the following linear programming model:

$$\begin{gathered} \min \xi^L, \text{ s.t.} \\ |w_B - a_{Bk} w_k| \le \xi^L, \text{ for all } k \\ |w_k - a_{kW} w_W| \le \xi^L, \text{ for all } k \\ \textstyle\sum_k w_k = 1, \ w_k \ge 0, \text{ for all } k. \end{gathered} \tag{2}$$

Using ξ^L, it is possible to calculate a consistency ratio (CR), which must not be higher than 0.25. As in AHP, global weights (w_k) of the base AEIs are calculated by multiplying the local weight of each AEI by the priority of its associated principle.

The PA method is a straightforward weighting technique that has proved valuable for determining the priorities of the different attributes of sustainability composite indicators [40,53]. In this method, the expert is asked to directly allocate a fixed number of points (e.g., 10 or 100) among the multiple criteria (indicators in our case) considered in a decision problem to establish the weight of each criterion [54]. In this paper, we apply this method as follows: first, each expert has to distribute 100 points between the two principles related to the environmental sustainability of irrigated olive grove (biodiversity protection and conservation of natural resources); second, experts allocate another 100 points among the five AEIs linked to biodiversity protection and an additional 100 points among the six AEIs related to the conservation of natural resources. Third, the global weights of the AEIs (w_k) are obtained (in percentage terms) by multiplying the priority of each AEI by the priority of its related principle.

3.3. Data Collection for the Empirical Assessment of Environmental Sustainability

The empirical assessment of the environmental sustainability of the irrigated olives groves in Spain relies on two data gathering sources: a survey of farmers to collect the farm-level technical data needed to calculate the AEIs considered (I_k), and a survey of experts to obtain the weights assigned to each of these indicators (w_k).

3.3.1. Farmer Survey

Due to the dispersion of the olive orchards in Spain, we carried out multi-stage cluster sampling to obtain a representative sample of irrigated olive farms. First, following a random selection of agricultural regions proportional to the total area of olive groves, six agricultural regions in Andalusia were selected (Andalusia accounts for more than 80% of total Spanish olive oil production). Figure 1 shows their location on a map. Second, a number of farms proportional to the area of olive groves in the agricultural region were selected through quota sampling, taking into account the farm size. Third, the selection of olive growers to be interviewed was determined using random route sampling. This procedure yielded a final sample consisting of a total of 480 olive farms. Further details about the sampling procedure can be seen in [23].

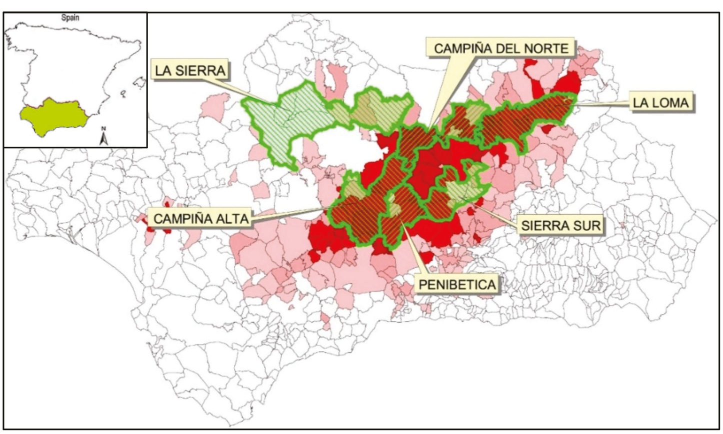

Figure 1. Location of the six agricultural regions included in the survey.

The data collection was carried out via face-to-face interviews with the farmers (lasting around 35 min each) using a structured questionnaire with nine blocks: (1) farm characteristics (location, area of irrigated and rainfed crops, ownership type and farm labor); (2) olive growing characteristics (varieties, plantation age, tree density, type of management: conventional, integrated or organic– and yield); (3) soil and weed management (agricultural practices, weed control—tilled or not tilled— and use of cover crops); (4) olive-pruning (date and desuckering debris management); (5) irrigation system and use of water-soluble fertilizers; (6) fertilization (fertilizers and dosage); (7) crop protection (chemicals, dosage, and management plans); (8) olive harvest (manual or mechanical); and (9) farmer's socio-economic characteristics (gender, age, professional experience, family size, income share from agriculture, education level, membership of producer organizations, and generational renewal). This information allowed us to calculate the corresponding AEIs (I_k) at the farm level.

The sample of 480 farms is divided into four types of olive orchards: traditional mountain olive groves (rain-fed), traditional low-medium slope olive groves (rain-fed), semi-intensive irrigated olive groves and other types. In this study, the assessment of environmental sustainability focuses on the semi-intensive irrigated type and is based on a subsample of 99 olive farms. The Table 2 summarizes farms' and farmers' characteristics in this subsample:

Table 2. Descriptive statistics from the farmer survey (n = 99).

Category	Variable	Mean	St. Dev.
Farm plantation	Olive grove area (ha)	17.2	26.5
	Plantation density (trees/ha)	98.0	23.0
	Plantation age (years)	99.5	101.2
	Average production (kg of olives/ha·year)	6146	1529
Farmers	Age (years)	50.8	10.7
	Time devoted to agriculture (%)	54.7	42.2
	Family labor (person-days/ha·year)	4.9	8.9
	Hired labor (person-days/ha·year)	5.9	8.7
Farm AEIs related to biodiversity protection	Number of olive grove varieties	1.75	0.81
	Index of biological diversity (dimensionless, [0,1])	0.59	0.18
	Pesticide risk (kg live organism/ha·year)	3666	2314
	Percentage of land with other crops (%)	4.77	13.23
	Percentage of non-cultivated land (%)	0.50	2.14
Farm AEIs related to natural resources conservation	Soil erosion (t soil/ha·year)	9.01	6.10
	Soil organic matter (dimensionless, [0,1])	0.71	0.28
	Nitrogen balance (N kg/ha·year)	−7.27	51.93
	Residual herbicide use (kg active matter/ha·year)	839	670
	Irrigation water use (m^3/ha·year)	686	314
	Energy balance (MJ/ha·year)	9990	4387

Source: Own elaboration based on farmer survey.

3.3.2. Expert Survey

In order to weight the contribution of each AEI to the composite indicator measuring the environmental sustainability of olive farms (*ENV_SUST*), a multidisciplinary group of 22 experts was selected following a judgmental sampling method [55]. The expert panel was primarily composed of scientists from universities and research centers (15), but also contained specialists from the Regional Administration (3) and technical services firms (4). Although it is a non-probability sampling technique, the nature of the technical information required and the homogeneity of the group (in terms of their expertise) suggest that the data gathering is reliable and bias-free [56].

The survey was based on one-to-one interviews, and two sessions were conducted with each expert. After an introduction about the objective of the study and the assessment methods, the questionnaires designed for each of those methods (AHP, BWM and PA) were administered. Each interview took approximately 20–30 min. Since the AHP questionnaire was slightly longer than the one for BWM, the short questionnaire conducted for the PA method was included in the BWM session. To avoid order effects (period and carryover effects), a counterbalanced Latin square design was followed [57,58]. Thus, half of the experts were given the AHP questionnaire first, whereas the other half began with the BWM and PA methods (controlling for the period effect). Then, two days later, the experiments were reversed for each group of experts (controlling for the carryover effect).

Finally, it is worth pointing out that from these questionnaires we obtained the individual AEI weights according to each of the three methods used, for each expert in the panel (w_{kj}), with the subscript k denoting the base indicator and the subscript j denoting the expert considered. However, the weights to be included in Equation (1) are the result of the synthesis of the panel's weights. In this regard, we follow Forman and Peniwati [59], who suggest that group decision-making should be performed by aggregating individual weights using the geometric mean for every weighting method (AHP, BWM and PA):

$$w_k = \sqrt[J]{\prod_{j=1}^{j=J} w_{kj}}. \quad (3)$$

4. Results

4.1. Indicator Weighting

The values of the consistency ratios for AHP and BWM, although not reported here due to space constraints, do not exceed the permissible threshold levels and, hence, provide evidence of the high degree of reliability of the experts' responses.

Table 3 shows the summary statistics of the global weights obtained by the three methods implemented (AHP, BWM and PA).

Table 3. Central tendency (mean) and variability (coefficient of variation, CV) of AEI global weights by weighting method.

AEI	AHP		BWM		PA	
	Mean	**CV**	**Mean**	**CV**	**Mean**	**CV**
Biodiversity protection						
NUMVAR	0.021	119.6%	0.025	67.7%	0.029	76.1%
DIVERSIND	0.146	53.3%	0.145	52.8%	0.142	41.8%
PESTRISK	0.104	82.2%	0.078	92.9%	0.085	76.2%
OTHERCROP	0.066	83.2%	0.067	60.7%	0.070	58.0%
NONCULTIV	0.088	83.9%	0.111	76.7%	0.099	57.3%
Natural resources conservation						
EROSION	0.201	51.2%	0.206	43.8%	0.176	46.2%
ORGMAT	0.112	68.6%	0.113	63.1%	0.112	52.0%
NITROGBAL	0.055	63.7%	0.058	51.3%	0.072	38.4%
RESHERB	0.074	105.5%	0.065	71.2%	0.075	65.1%
WATERUSE	0.084	92.1%	0.074	68.5%	0.082	60.8%
ENERGYBAL	0.050	97.9%	0.058	73.4%	0.058	70.4%
Mean		81.9%		65.6%		58.4%

Source: Own elaboration based on expert survey.

There is consensus about the most important AEI for the protection of biodiversity; namely, the index of biological diversity (*DIVERSIND*). This is followed by the pesticide risk (*PESTRISK*) for AHP, and by the percentage of non-cultivated land (*NONCULTIV*) for BWM and PA. Regarding the second principle, the conservation of natural resources, there is also consensus about the most important indicator, soil erosion (*EROSION*), followed by soil organic matter (*ORGMAT*). It is worth noting that the lowest variability of AEI weights is found with the PA method.

4.1.1. Inter-rater Reliability

Before undertaking the comparison of the weighting methods, we assess the degree of agreement between the experts' AEI weights, using the intraclass correlation coefficient (ICC). Unlike the traditional correlation coefficient, based on paired observations, the ICC simultaneously considers the group agreement. Higher ICC values indicate higher inter-rater reliability, with 1 indicating perfect agreement and 0 only indicating random agreement [60]. There are 10 different forms of ICC depending on: (1) the statistical model; one-way or two-way models, according to whether the source of variation comes from objects or subjects (raters), respectively; (2) whether raters are considered as random or fixed effects (two-way random-effects model or two-way mixed-effects model, respectively); and (3) the type of agreement: absolute agreement (for the same object, similar scores among raters) or consistency (for the same object, similar ranking among raters) [61,62].

Since the experts are not randomly selected and we are interested in assessing whether or not the AEI weights are equal within each weighting method, we estimate the absolute agreement among experts using a two-way mixed-effects model. The resulting ICCs for AHP, BWM and PA are presented in Table 4.

Table 4. Intraclass correlation coefficients and 95% confidence intervals for the three methods.

Weighting Method	ICC(3,k) Coefficient	Lower Bound	Upper Bound
AHP	0.89	0.82	0.96
BWM	0.93	0.87	0.97
PA	0.92	0.85	0.97

Source: Own elaboration based on expert survey.

To interpret ICC, Cicchetti [63] gives some guidelines: <0.40, 0.40–0.59, 0.60–0.74, and >0.74 for poor, fair, good and excellent reliability, respectively. Additionally, Koo and Li [64] give slightly different intervals: <0.5, 0.5–0.75, 0.75–0.9 and >0.9 for poor, moderate, good and excellent reliability, respectively. In our case, the degree of agreement can be regarded as good to excellent in all three methods. Thus, despite the sample size limitation, all three methods produce consistent assessments of AEI weights. Notwithstanding these outcomes, as commented above, PA produces the least variability in experts' assessments in terms of the coefficient of variation (see Table 3).

4.1.2. Multivariate Comparison of Weights from the Three Methods

In order to compare the AEI weights from the three methods, a within-subjects multivariate analysis of variance (MANOVA) design was implemented. The MANOVA not only reduces the chance of Type I error but can also account for the correlation among the dependent variables [65], and therefore has more power to detect differences among groups [66,67]. The experimental design met the assumptions relating to the measurement of the dependent variables at interval scale, the independence of observations, and adequate sample size (more observations than the number of dependent variables; in this case, 22 observations vs. 11 variables).

Regarding the additional assumptions of the MANOVA, we conclude: (1) the visual check of scatterplots suggests that the condition of linearity (no curvilinear pattern between all pairs of indicators) is met; (2) the conditions of homogeneity of variance-covariance matrices (Box'M statistic = 124.0, p-value = 0.686) and homogeneity of variances (minimum Levene statistic = 0.895, p-value = 0.414) are fulfilled; (3) there is no multicollinearity among the AEIs (maximum r = 0.580 < 0.90 [67]); (4) none of the three methods satisfy the multivariate normality assumption, however, since we have equal group sizes, the MANOVA is robust given the absence of multivariate outliers [68,69]; and (5) no multivariate outliers were identified using Mahalanobis distance (minimum probability equals 0.066). According to this evidence, the MANOVA can be applied to check for significant differences of means among weighting methods. The results of the MANOVA are shown in Table 5.

As Table 5 shows, three out of four multivariate criteria test statistics suggest there is no statistically significant difference in means. Furthermore, as Kuhfeld [70] points out, in the event of a discrepancy between Roy's Largest Root and the other three test statistics, the effect should be considered to not be significant. In summary, the results suggest that the AEI weights do not depend on the weighting method (AHP, BWM, and PA).

Table 5. Multivariate comparison of AEI weights by weighting method.

Within-Subjects Effect		Value	F	Hypothesis d.f.	Error d.f.	*p*-Value
Statistic	Pillai's Trace	0.541	1.441	18.000	70.000	0.140
	Wilks' Lambda	0.522	1.449	18.000	68.000	0.138
	Hotelling's Trace	0.794	1.455	18.000	66.000	0.136
	Roy's Largest Root	0.589	2.289	9.000	35.000	0.039

Source: Own elaboration based on expert survey.

It is subject to discussion whether the consistency of the three methods depends on the use of the same group of experts. Although further research would be needed in this regard, a random subsampling of the 22 experts was carried out (assigning 8 to AHP, 7 to BWM, and 7 to PA) to compare the AEI weights, yielding the same conclusion based on the MANOVA test (*p*-values: 0.190, 0.256, 0.338 and 0.158, respectively).

4.2. Assessing the Environmental Performance of Irrigated Olive Farms

Table 6 shows the main descriptive statistics of the 15 distributions of the composite indicator *ENV_SUST* (3 weighting methods × 5 values of lambda) obtained for the 99 olive farms sampled. As can be clearly observed, the index values calculated vary more due to the compensation parameter λ than due to the weighting method. In fact, while there is no statistically significant difference among the means and the variances of the *ENV_SUST* distributions obtained for every single λ, it can be proved that the average values significantly decrease as the compensation parameter decreases.

Table 6. Descriptive statistics of the composite indicator (*ENV_SUST*) by compensation parameter (λ) and weighting method.

	Method	Mean	Min.	Max.	St. Dev.	CV
$\lambda = 1$	AHP	0.549	0.140	0.783	0.118	21.5%
	BWM	0.533	0.151	0.782	0.116	21.9%
	PA	0.536	0.106	0.777	0.120	22.3%
$\lambda = 0.75$	AHP	0.414	0.105	0.587	0.090	21.8%
	BWM	0.402	0.113	0.587	0.089	22.1%
	PA	0.404	0.079	0.582	0.091	22.6%
$\lambda = 0.5$	AHP	0.278	0.070	0.512	0.066	23.6%
	BWM	0.270	0.076	0.496	0.065	23.9%
	PA	0.272	0.053	0.510	0.066	24.4%
$\lambda = 0.25$	AHP	0.143	0.035	0.483	0.050	35.0%
	BWM	0.139	0.038	0.475	0.050	35.7%
	PA	0.139	0.026	0.482	0.050	36.1%
$\lambda = 0$	AHP	0.007	0.000	0.454	0.052	700.9%
	BWM	0.007	0.000	0.454	0.052	696.6%
	PA	0.007	0.000	0.454	0.052	718.5%

Source: Own elaboration based on expert and farmer surveys.

Although the discussion about the most suitable value of the compensation parameter to measure farms' environmental performance is beyond the scope of this paper, it is worth pointing out that composite indicators based on complete compensability (i.e., $\lambda = 1$) have been criticized because trade-offs between base indicators could be considered incompatible with the concept of sustainability [13,40]. It is thus reasonable to opt for indexes that allow partial compensability (i.e., *ENV_SUST* for $0 < \lambda < 1$). In any case, the selection of the most suitable value of λ is an issue that remains open for discussion in future studies [18].

The assessment of the rankings of farms produced by the composite indicator *ENV_SUST* using the three weighting methods, for each of the five values considered for the compensation parameter ($\lambda = 0$, $\lambda = 0.25$, $\lambda = 0.5$, $\lambda = 0.75$ and $\lambda = 1$), is carried out using the Kendall's coefficient of concordance, or Kendall's W [71], mathematically:

$$W = \frac{12S^2}{m^2(k^3 - k)} - \frac{3(k+1)}{k-1}, \quad (4)$$

where $m = 3$ (AHP, BWM, and PA), $k = 99$ (number of farms), r_{ij} = ranking of farm i by method j, $R_i = \sum_{j=1}^{m} r_{ij}$ and $S^2 = \sum_{i=1}^{k} R_i^2$. To test the null hypothesis of no agreement among the methods, that is $W = 0$, the statistic to be used is $m(k-1)W \sim \chi^2_{k-1}$.

As the results in Table 7 show, the ranking of the irrigated olive farms based on their environmental performance (i.e., values of composite indicator *ENV_SUST*), for any lambda considered, does not depend on the weighting method used (AHP, BWM, or PA). Furthermore, when considering the 15 rankings simultaneously, the overall Kendall's W indicates a strong level of concordance (Kendall W's = 0.705). This indicates that, regardless of the weighting method or the compensation parameter, all *ENV_SUST* measurements provide similar rankings of the sampled irrigated olive farms.

Table 7. Kendall's coefficient of concordance of farms' sustainability ranking with the three weighting methods.

	Compensation Parameter					
	$\lambda = 1$	**$\lambda = 0.75$**	**$\lambda = 0.5$**	**$\lambda = 0.25$**	**$\lambda = 0$**	**Overall**
Kendall's W	1.000	0.987	0.988	0.988	1.000	0.705
p-value	0.000	0.000	0.000	0.000	0.000	0.000

Source: Own elaboration based on experts' and farmers' survey.

5. Conclusions

Measuring environmental sustainability in agriculture through the construction of composite indicators is a widespread practice, although it is a tough task. An especially challenging aspect is the choice of the most appropriate methods to normalize, weight and aggregate the large set of base agri-environmental indicators usually considered. In particular, the results of environmental composite indicators are heavily dependent on how the base indicators are weighted (i.e., if the indicator weights can accurately synthetize the relative importance of each AEI included in the index built). For this reason, our main aim in this paper was to analyze the robustness of three alternative weighting methods (AHP, BWM and PA). To that end, we consulted the opinions of a panel of experts and compared the results obtained for an environmental index implemented in the real-world case study of irrigated olive farms in Spain.

In light of the results, we can identify three main findings: first, there is a high level of consistency in experts' assessments of AEI weights derived from the three weighting methods; second, there are no statistically significant differences in the means of the AEI weights estimated with the three methods; and third, the values of the composite indicator built (*ENV_SUST*) using the three alternative weighting techniques produce similar rankings of the irrigated olive farms in terms of their environmental performance. Further evidence regarding the consistency of the weighting methods is needed to confirm whether this finding is generalizable. In any case, it can be hypothesized that similarly consistent results can be expected whenever the composite indicator construction (i.e., weighting) is focused on the assessment of technical concepts, where expert opinion is rooted in empirical knowledge.

Overall, these findings provide useful empirical insights into the robustness of the two multicriteria methods, AHP and BWM, and the more straightforward PA, as weighting techniques to be used when constructing composite environmental indicators. However, although the three methods are valid, feasible tools to determine the weights of the individual base indicators, it is worth noting that the PA could be cumbersome if there is a large number of indicators to be included in a single index (e.g., more than six) [44].

Beyond the methodological focus, it is also worth pointing out that the *ENV_SUST* composite indicator implemented in this study is sufficiently stable and methodologically sound to be used in the design of targeted policy interventions aimed at measuring the environmental sustainability of farms. In this context, there is still room for research on the practical implementation of this environmental index to analyze the heterogeneous environmental performance among farms (i.e., determining reference and threshold values) and track changes in agricultural practices (i.e., irrigation or fertilization). This practical information could be useful for policy-makers in the design of the results-based agri-environmental programs, to set the level of payments to be granted to each particular farm or any other policy instruments with a similar purpose (i.e., fiscal or qualitative rewards).

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Sustainability in Forest Management Revisited Using Multi-Criteria Decision-Making Techniques

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Abstract: Since its origins, the idea of sustainability has always been linked to forest management. However, nowadays, sustainable forest management has usually been approached by defining a set of criteria and indicators. This paper aims to address sustainability in forest management including a set of criteria encompassing the most common decisions: whether the stands are even or uneven-aged, and the optimal silviculture that should be applied in each stand. For this purpose, a lexicographic goal programming model with two priority levels has been defined, into which six different criteria are integrated. Each criterion corresponds to a particular pillar (economic, technical, or environmental). Furthermore, also incorporated into the model are the preferences of diverse stakeholders, both for the criteria considered in the analysis and for the most suitable silvicultural alternatives to be applied in each stand. This methodology has been applied to a case study in Spain, and the results show much more attractive solutions than the current forest management planning, allowing the obtainment of multi-aged systems that could be favourable for other ecosystem services.

Keywords: goal programming; interactive methods; forest planning; Green-Tree Retention

1. Introduction

The concept of sustainability in a forestry perspective has a development history that dates over 300 years back in time [1], without the author himself having supplied any definition of this term [2]. In some respects, this idea at that time was the first conservation principle ever formulated [3]. In recent decades, it has spread in an exceptional manner to other areas [4]. To some authors, the sustainability concept is currently belonging to the field of social ethics [5]. Nowadays, it continues to be a forceful message with a wide representation in diverse disciplines [6]. In synthesis, von Carlowitz's premise promoted the concept of not exhausting resources in order to bequeath them to future generations, safeguarding finite natural resources for future generations [7].

In order to integrate sustainability into forest management, it has been customary to define a multidisciplinary ensemble of criteria and indicators in order to arrive at a consensus as to what sustainable forest management should be like [8], although sometimes it is not easy to transfer this idea to a strategic level [9]. It has been successfully applied on different spatial scales, using more or less aggregated information. Thus, there are indicators for sustainable forest management focused at a national or supranational level [10,11], or at a management unit level [12,13]. Further, in order to include this concept of sustainability in forest management, tools like certification systems aimed at ensuring sustainable management in forests have been developed. Thus, the systems most used nowadays simply require compliance with a series of indicators [14]. However, although it is commonly believed that a certification scheme implies a sustainability attribute, this direct relationship is not always clear [15].

On the basis of the literature consulted, it has been verified that the definition of sustainable forest management was usually of a static nature. That is to say, the studies in question contained only one measurement of the indicators, without taking into account their temporal evolution, in spite of this component being included in the definition of the word sustainability [16]. However, only in some studies has it been proposed to measure a set of criteria over the entire planning horizon covering forest management in a certain case study [17–19]. Given the extensive length of rotations in many forest systems, it is necessary to have a set of indicators available whose values are known in each period or, at least, are quantifiable at the end of the planning horizon.

Given the multidimensional nature intrinsic to the concept of sustainability, and as has been mentioned previously, the need to apply multifunctional management requires the use of Multi-Criteria Decision-Making (MCDM) techniques. These methodologies have been widely employed to solve typical forest management problems [20–22]. Moreover, multicriteria methods have been applied prolifically to tackle aspects related to sustainability [23–26], even dealing with aggregation problems and dynamic sustainability indicators [27]. These methodologies are also recommendable for integrating different ecosystem services into the decision-making process [28–30]. Finally, it is fitting to insist that these methods permit the solution of the emergent problem of how to aggregate the indicators on which the idea of sustainability is based [31].

Bearing in mind that sustainability is difficult to define in precise terms [32,33], the main objective of this study is to present a flexible model, based on multicriteria techniques. These kinds of models permit the redefinition of sustainability in a forest system, not at one specific moment, but through the evolution of the indicators considered throughout the planning horizon. This new view of sustainability should address the multifunctionality of forest systems, which implies defining a diverse set of criteria and indicators, choosing the best silvicultural alternative for each stand, and enabling the stakeholders involved to have their opinion integrated into it. It should be emphasized that some authors have affirmed that the rigidity of the concept of a normal forest does not ensure the idea of sustainability in force today [34], which would justify using the approach proposed here in order to adapt this notion to the present-day context. Finally, in the following Sections, we will introduce terms like "criterion", "objective", "indicator" and "index". In order to avoid misinterpretations, and following [35], under an MCDM umbrella, criteria are the objectives or goals to be considered relevant for a certain decision-making situation. However, if applicable, we have considered a hierarchy between criteria and indicators. Indicators are parameters or sub-criteria which can be measured, and which correspond to a particular criterion. Besides, some sustainability measurements can be defined as a synthetic, aggregate, or composite index, and the value achieved by this index is a proxy of the respective sustainability goodness.

2. Theoretical Background

2.1. Framework

The stages of the model proposed are condensed in Figure 1A. The first step involves defining both the sustainability indicators selected for the planning horizon chosen, and the different silvicultural alternatives put forward. Applying both the indicators and the silvicultural alternatives to the case study, precise information is made available for the formulation of a strategic forest planning model. If each criterion considered is optimized separately, the pay-off matrix can be set up and the degree of conflict between the different criteria verified [35]. If no solution is supplied by the pay-off matrix, coming from the optimization of a single criterion is acceptable. The following step is to construct an MCDM model, integrating the opinions of the stakeholders (DMs) on some aspects. In that way, compromise solutions that could be accepted by the decision-maker will be obtained.

As previously mentioned, the methodology to be applied is based on MCDM techniques, because the latter are highly appropriate when facing this type of problem. However, although, under the MCDM umbrella, a large set of techniques co-exist [36], due to the nature of the problem, only those that can solve continuous-type problems will be apt. This circumstance implies that those techniques that aim to choose the best solution out of a finite set of alternatives would not be valid for this case. From the MCDM techniques that fulfil the above condition, goal programming has been selected. This methodology adds flexibility to forest management models [37], and it has been used quite frequently to tackle this type of problem [31]. The basics of goal programming can be seen in [38–40].

Among the variants of this technique typically employed [39], we chose Lexicographic Goal Programming (LGP), also known as Non-Archimedean or pre-emptive goal programming [41]. The selection of this technique is justified because it allows the decision-making centre to show an order of preference for each of the goals defined. In addition, the idea of defining sustainability by means of a conceptual hierarchy [42] fits the LGP notion perfectly. This hierarchy manifests itself in the definition of different levels of priority to which each goal is attached. This means that the preferences are initially assigned to each goal following an established order, and that the achievement of a goal situated at a certain level of priority is infinitely preferred to the fulfilment of one located at a lower priority level. In short, this type of modelling implies accepting that there are no finite trade-offs among the goals placed at one priority level with respect to goals placed at lower ones [35]. Consequently, the results obtained for the goals situated at lower priority levels cannot worsen those of the goals at higher priority levels [43]. The mathematical formulation can be seen in Appendix B**.** Once the goals are defined [44], the variant of the weighted goal programmed is selected to solve the problem at each priority level [45], this being the most common option when electing this goal programming variant [46].

With the methodology shown in Appendix B, a model is obtained which permits the evaluation of the different criteria or indicators considered for defining sustainability over the defined time period, in the context of strategic forest planning [9]. The preferences introduced into the model will only take into account the opinion of the stakeholders and exclude intergenerational justice components from the analysis [47]. In addition, only criteria for which values can be obtained throughout the entire planning horizon are considered [31]. That is to say, if the evolution over time of a certain criterion cannot be modelled, it is not included in the analysis. Further, it is assumed that the silvicultural alternatives that can be applied in each of the stands are known with certainty. The model proposed is totally deterministic, and the introduction of elements of risk and/or uncertainty is not considered [48–50]. Finally, although, in previous work, diverse climate change scenarios have been analyzed in the same case study [51,52], the latter will not be included in this work, although the results for some ecosystem services like carbon sequestration could be altered according to the different scenarios contemplated [53].

The next step is to design a strategic forest planning model (see Appendix B). In order to assess the degree of conflict between the criteria considered, a pay-off matrix was developed starting from the results of the strategic forest planning model. This is a usual step in the application of multicriteria techniques in forest management problems [54,55]. The pay-off matrix is a square matrix, whose dimension coincides with the number of objectives considered. This matrix is obtained by optimizing the six objectives separately and computing the values of the criteria for each of the corresponding optimal solutions, thus having a dimension equal to the number of objectives that exist [35]. The main diagonal includes the optimum values that each objective can reach, known as the ideal point. By definition, this vector in the objective space is infeasible, but plays a decisive role as a point of reference [56]. Other cells of the matrix contain the anti-ideal (nadir) points, which would be the worst results obtained for each of the objectives. Concerning the criteria considered, it is appropriate to clarify that *VOL*, *NPV*, *IM* and *C* are criteria belonging to the type "the more, the better", while *NF* and *G* are criteria belonging to the type "the less, the better", following the term used in [35].

2.2. Theory Review

The primordial concept of sustainability has marked the development of forest science both in Europe and in the U.S.A. [57], and it has become a leading component of forest management over the last 250 years [58]. Similarly, it has been considered to be an integral part of forest management [33] and has been accepted almost unanimously by foresters [59]. Generally, in the past, sustainability was based on a few basic principles in accordance with the type of forest management practiced at the time, which was centered on the "normal forest" or "normality" concept [60], established at the end of the 18th century by German foresters [61]. In fact, it was characterized by being a mono-objective management, focused only on timber production, usually in regular stands, in which one or a few main species prevailed [62], and to which a silviculture with a fixed rotation was applied [63]. In addition, a single decision-maker made the corresponding decisions with the aim of perpetuating the idea of a fully-regulated forest [57,64]. Finally, as a result, and unlike what happens nowadays [65], restrictions to final harvest were very lenient.

The concept of sustainability has been modified and updated due, among other reasons, to the changes in the role played by forests in society [66,67]. Besides that, the demand for goods and services coming from forest systems has been continuously increasing [68], meaning that, today, forest management is much more polyhedral (or multi-faceted, according to [69]) than it was three centuries ago, and includes other ecosystem services not contemplated in the original idea of sustainability, such as in the case of biodiversity [70]. Indeed, some authors have recently gone beyond the theory of von Carlowitz and defined forests as a "multifunctional bioeconomic system" [71]. Thus, numerous authors maintain that the new paradigms associated with sustainability should promote multifunctionality in forest management [72]. At the same time, the idea of sustainability in forest management has been linked to that of resilience [73]. In this regard, although the expression "sustainable" has for many years been on a par with forest management [74], nowadays it has been assumed that the latter should achieve certain goals with respect to economic, social and environmental pillars and, also, balancing present and future demands [75]. Some authors even propose the concept of "ecologically sustainable forest management" to give prominence to a type of forest management that perpetuates ecosystem integrity [76].

The way forest management has evolved has required the reformulation of the original sustainability concept [1] into the idea of a "regulated forest" (the organization of a forest property to provide a sustained yield of timber products forms [57]), by integrating the abovementioned pillars, but taking into account that, on some occasions, the trade-offs between different criteria are not fully known [77]. That is why sustainability should not be defined by only focusing on the conception of its being concentrated on "sustained yield", one of the objectives most sought after in forest management [78], or on other similar concepts [47]. Namely, this idea should be generalized starting from a case in which not all the forest should be associated with the idea of even-aged stands into which different silvicultural alternatives are established [63]; other ecosystem services are integrated, as well as timber production; and the preferences of the different stakeholders in the decision-making process are included. In effect, a multi-aged structure in forest stands is associated with the idea of long-term sustainability [79], incorporating multiple uses into different stands even with variable rotations [32]. Lastly, the inclusion of different silvicultural alternatives in the analysis is basically justified for two reasons. First, because different forest management strategies promote biodiversity [80], and, second, because silviculture as a science has to respond to the demands of society and not only concentrate on timber production [81].

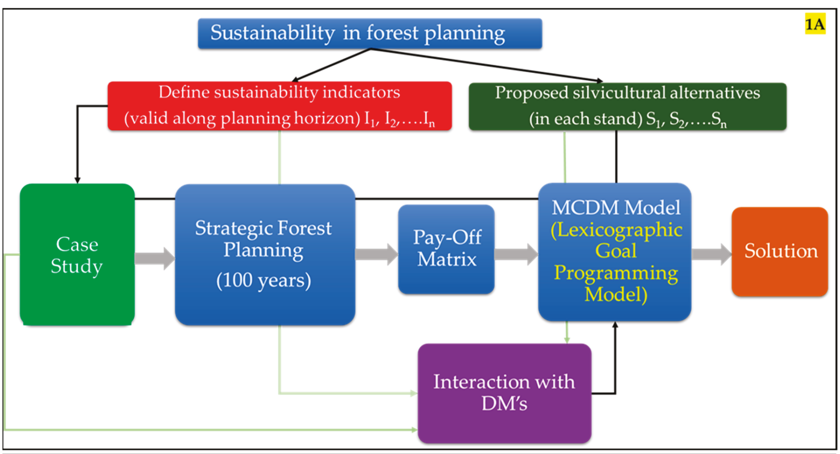
3. Materials and Methods

3.1. Case Study

The case study corresponds to Valsaín forest, which is in the Central Mountain Range of Spain. The forest area covers about 7206 ha and mainly composed of pure Scots pine (*Pinus sylvestris* L.) stands, although there are other species less represented in the area such as *Quercus pyrenaica* L. and *Ilex aquifolium* L. The first management plan was developed in 1889, and the main objective was timber production. Since 1940, in order to achieve this objective, a uniform shelterwood system with a rotation of 120 years and a 20 years regeneration period has been proposed [52]. However, in recent years, this management has become more multifunctional [25], and the silvicultural treatment was turned into a shelterwood group system [52]. Nowadays, other aspects such as biodiversity conservation are of great importance. Thus, there are several endangered species in the area, like the black vulture (*Aegypius monachus* (Linnaeus, 1766)). The number of nests of this species is around 131, and harvest limitations have been introduced in order to protect them. In short, around each nest, a restricted area without management of 3.14 ha has been established as a buffer protection. Finally, there are several protection features in this forest, such as the declaration of the Sierra de Guadarrama National Park in 2013, where commercial cuttings have been forbidden, and which affects 3326 ha.

3.2. Silvicultural Alternatives

In order to deal with this complexity, seven silvicultural strategies have been proposed to maintain the adaptability of forests to different conditions [81], and to provide different ecosystem services. The set of possible treatments considers the nature of the stands forming the case study, and all of them have been discussed and approved by the forest manager. A priori, the seven treatments (see Figure 1B and Appendix A, Table A1) could be applied to every stand.



Define sustainability criteria (valid along the planning horizon)

Criterion	Acronym	Meaning
Normal Forest	*NF*	Represents the idea of a normal forest based on three indicators (final cuts similar in each period, final inventory, and regulation), that, suitably normalised, fulfil this aggregated and dimensionless criterion.
Ideal Management (ha)	*IM*	Represents the extent of the area on which the appropriate silviculture is applied in accordance with the objective sought in each management unit, following the preferences declared by the decision-maker.
Gini index	*G*	Represents a measurement of inequality. The idea of including this index lies in promoting the existence of an uneven-aged stands trend as a conservation measure.
Carbon balance (tC)	*C*	Difference between the estimated of gains and losses of carbon due to the growth of trees and the emissions produced after the final cuttings over the planning horizon.
Harvest volume (m^3)	*VOL*	Volume harvested under the different silvicultural treatments proposed over the planning horizon.
Net Present Value (€)	*NPV*	Economic criterion derived from the timber cuttings.

Proposed silvicultural alternatives (in each stand)

Silvicultural alternative*	Acronym
Business as usual 1	BAU1
Business as usual 2	BAU2
Group Selection	GS
Green Tree Retention 1	GTR1
Green Tree Retention 2	GTR2
Treatment for National Park	TNP
No Management	NM

*more information in Appendix A (Table A1)

1B

Figure 1. Framework for integrating sustainability into forest planning (**1A**). Sustainability criteria and silvicultural alternatives proposed (**1B**).

The first alternative is based on a shelterwood group system. The treatment spans 40 years, cutting every ten years, and it would be the "business as usual" alternative (BAU). After the final cut, 2% of the stand volume remains as dispersed trees for at least one rotation. In order to model this alternative, we have considered the schedule and cutting intensity traditionally used in Valsaín forest [82]. BAU has been divided into two new alternatives: BAU_1, embracing light thinning, and a more intensive option with strong thinning (BAU_2). The third alternative, called Group selection (GS), consists of 2 cuttings with medium patch sizes of 1 hectare. After final cutting, 5% of the stand volume remains as residual trees.

Another two silvicultural alternatives are based on the idea of Green Tree Retention (GTR). Two GTR alternatives with different retention percentages are proposed, before applying BAU_1 or BAU_2. In short, either 15% of the volume is maintained in an aggregated way as mature forest patches (GTR_1), or 30% of it (GTR_2). These figures are similar to those proposed for this species in Spain [83]. These patches could simulate the protection buffers discussed above for the protection of the black vulture species.

For the area now included in the National Park, we have proposed an alternative (TNP) similar to BAU, but with a main difference: the final cut is excluded, due to prohibitions in all Spanish National Parks. Moreover, in this case, the rotation has been increased (up to 140 years) in relation to the other treatments, as a conservation measure [84]. Finally, a no management alternative (NOM) has been incorporated in order to facilitate the possibility of creating mature forest stands in the future, given that these stands are allowed to grow naturally, thus forming reserve areas.

3.3. Criteria Considered

As mentioned above, the criteria to be introduced should evaluate sustainability based on the multifunctionality intrinsic to forest systems. First, two technical criteria have been defined. The first of these corresponds to a synthetic index that encompasses the classic idea of a normal forest (NF). In short, this criterion embraces tree indicators: one associated with the notion of even-flow policy, another with the idea of regulation or regulated forest [57], and, finally, a third one related to a suitable ending forest inventory, which ensures the perpetuation of the forest. In order to aggregate the above indicators under the normal forest concept, the procedure used in [85] was followed. In addition, a criterion called Ideal Management (*IM*) has been introduced. It can be quantified by the amount of area (in hectares) to which the silviculture suitable for each stand, according to the criterion optimized in each case, is applied. Therefore, calculating this criterion consists of minimizing the deviations of the silviculture used, compared to that which would be preferred in terms of the characteristics of the stands and in accordance with the preferences reflected by a decision-maker.

On another side, two environmental criteria have been defined. The first one refers to the possibility that, at the end of the planning horizon, there is a multi-aged forest. To enable a comparison of the degree of irregularity between different prescriptions, the Gini index (*G*) was employed. The latter is frequently used to measure the degree of inequality in different variables, generally with economic data, although applications in many fields have been described [86]. It supplies values in the interval [0 1] and has been defined in such a way that values close to 0 imply the existence of multi-aged stands, whereas values close to 1 ensure an even-aged structure. The second environmental criterion considered was the carbon balance (*C*), defined as the difference between the estimated gains and losses of carbon due to the growth of trees and their removal (default method, following [87]) throughout the planning horizon. This criterion will be computed in physical units (tons of carbon).

With respect to the production criteria, the Net Present Value (*NPV*) and the volume (*VOL*) associated with the final cuttings (cubic meters) over the planning horizon have been considered. Regarding *NPV* (€), the incomes provided referred only to timber sales. We have considered a fixed maintenance cost (11.6 €/ha), and different harvesting costs in relation to the silvicultural treatment applied. Following data provided from the current forest management plan, the timber price considered was 28 €/m^3. We have considered a real discount rate of 2%. Concerning the criteria considered, it is appropriate to clarify that *VOL*, *NPV*, *IM* and *C* are criteria belonging to the type "the more, the better", while *NF* and *G* are criteria belonging to the type "the less, the better", following the terms used in [35]. Figure 1B shows the six criteria considered with their acronyms, meanings, and the units in which they are expressed.

3.4. Multi-Criteria Model

When analyzing the solutions shown in the Pay-off matrix, if no solution is preferable, it is necessary to look for a satisficing compromise solution, making the harvest scheduling more sustainable. As we have said before, the technique chosen was Lexicographic Goal Programming (LGP), the second most used GP variant in forest management applications [88].

The first issue to decide in this type of model is how to select the number of priority levels that one wants to establish. Starting from the premise that it should be a limited number and that there should not be as many priorities as the number of criteria [89], in this case, two priority levels have been fixed. In the first one, three goals most directly related to silvicultural aspects have been included, while in the second, *NF*, *IM* and *G* are considered. Namely, given that there are no finite trade-offs among goals placed at the two priority levels [88], it is assumed to be a priority to achieve the goals at the first level before optimizing the criteria situated at the second priority level [90]. The target for each goal was established at 70% with respect to the ideal value obtained in the pay-off matrix. This percentage has been employed in the literature [91], and its use avoids the drawback of not obtaining optimal alternatives if the targets are closer to ideal values [92]. Finally, the complete model can be found in Appendix B, and for its resolution the software LINGO 13.0 [93] has been used.

3.5. Interactive Process

In this study, we interacted with two decision-makers (DM1 and DM2). First, as mentioned above (Equations (A2) and (A3)), it was considered appropriate to introduce preferential weights for each of the six goals contemplated in the analysis. For this purpose, the interaction was with the forest manager (DM1), and his opinion was asked on the six criteria using a survey based on pairwise comparisons, with Saaty's verbal scale [94] (see Appendix A, Table A3). This way of obtaining the decision-maker's preferences is recommended for integrating them into GP models [95]. These pairwise comparisons are typically used in the forest context [96].

On another side, and with the aim of obtaining the IM criterion, the engineer in charge of carrying out the last forest management planning (DM2) was contacted. Taking into account the silvicultural alternatives considered (see Appendix A, Table A1) the objective was to establish the suitability of each one for being applied to each stand. For this purpose, the 288 stands in the forest have been grouped into seven categories generated as a combination of a series of factors: production, protection, National Park, districts with nests or the presence of mixed stands. Once the categories were defined, in a first contact with DM2, we selected a set of 2–3 preferred alternatives for each stand. Later, after a second interaction with the same expert, some weights were obtained to weight the different silvicultural alternatives for their suitability, attending to the characteristics and nature of the stand in which they were found (see Appendix A, Table A2). To obtain the weights assigned to each silvicultural alternative in each stand, the same procedure as that employed with DM1 was used (see Appendix A, Table A3).

4. Results

Beginning with the pay-off matrix, Table 1 shows the results of the optimization of the six criteria separately. In Table 1, ideal values (principal diagonal of the matrix) are shown in bold type, while anti-ideal (or least desired ones) are underlined. The main diagonal includes the maximum values that each criterion can reach, known as the ideal point. Other parts of the matrix contain the anti-ideal points, which would be the worst results obtained for each of the criteria. Finally, to increase the informative character of this matrix, several additional rows were included by measuring the area occupied when each criterion is optimized by each of the silvicultural treatments described, as well as the average rotation.

Table 1. Pay-off matrix (ideal values in bold; anti-ideal values underlined).

Criteria	*NF*	*IM*	*G*	*C*	*VOL*	*NPV*
NF	**0.214**	1.195	1.185	1.175	2.737	1.574
IM	240	**5358**	1101	973	524	567
G	0.850	0.766	**0.360**	0.907	0.748	0.762
C	5661	5973	5789	**6697**	5097	5276
VOL	2981	2283	2695	659	**4245**	3846
NPV	29,063	18,515	28,526	7921	35,098	**61,384**
area-BAU_1	44	142	22	529	5126	5696
area-BAU_2	937	0	0	131	18	936
area-GS	4841	62	192	365	1630	164
area-GTR_1	30	2833	0	203	22	0
area-GTR_2	0	1226	6391	0	0	0
area-TNP	82	1932	191	0	0	0
area-NOM	861	600	0	5.568	0	0
Average rotation	147	166	143	150	159	126

NF: Normal Forest structure, ***IM***: Ideal management (ha), ***G***: Gini index, ***C***: Carbon balance (10^3 tC), ***VOL***: Harvest volume (10^3 m^3), ***NPV***: Net Present Value (10^3 €). area-BAU_1: area under BAU_1 treatment (ha), area-BAU_2: Area under BAU_2 treatment (ha), area-GS: Area under GS treatment (ha), area-GTR_1: Area under GTR_1 treatment (ha), area-GTR_2: Area under GTR_2 treatment (ha), area-TNP: Area under TNP treatment (ha), area-NOM: Area under NOM treatment (ha). *Average rotation* (years).

The results given in this table show the ideal and anti-ideal values reached by the criteria, according to the optimized criterion (per columns). First, it can be seen that some objectives do not reach ideal values (*NF*, *IM*, *G*). Then, the level of conflict existing between the different criteria, mainly between *NF* and *IM*, and between *C* and *G*, can be observed, as well as the fact that the results are fairly similar in relation to carbon balance, because the percentage for this criterion varies the least compared to the rest. In synthesis, it can be noted that there is no solution corresponding to the optimization of a single criteria that appears to be sufficiently attractive. In short, the results of this pay-off matrix justify the setting up of an MCDM model in order to achieve solutions that are more balanced from the point of view of sustainability.

However, before revealing the results of those models, the result of the first interaction with DM1 to obtain the preferential weights associated with the criteria is shown (Table 2). Note that the sum of the weights for each priority level is equal to 1. Finally, Appendix A (Table A2) contains the weights obtained throughout the second interactive process with DM2 for the seven categories, in which the stands and the silvicultural alternatives associated with them have been grouped.

Table 2. Preferential weights associated with the criteria after DM1 interaction.

Criteria	Priority Level	Preferential Weights
NF		0.078
IM	1	0.435
G		0.487
C		0.467
VOL	2	0.067
NPV		0.467

NF: Normal Forest structure, ***IM***: Ideal management (ha), ***G***: Gini index, ***C***: Carbon balance (tC), ***VOL***: Harvest volume (m^3), ***NPV***: Net Present Value (€).

Next, Table 3 displays the solutions obtained for the two priority levels proposed. It can be noted that the solutions at the second priority level ($\boldsymbol{U_2}$) are the same as the values found in the preceding solution (U_1), whereas the values of the three criteria included in U_2 improve in comparison with those obtained in U_1. Further, to facilitate comparisons, the same auxiliary rows have been included. In general, it can also be seen that the areas assigned to each silvicultural alternative are notably modified when moving from U_1 to U_2.

Table 3. Results obtained in the resolution of model LGP (in bold the results for the six goals considered).

Criteria	U_1	U_2
NF	**0.56**	**0.56**
IM	**3750**	**3750**
G	**0.67**	**0.67**
C	**5599**	**5605**
VOL	**2735**	**3120**
NPV	**27,294**	**42,969**
area-BAU_1	384	1667
area-BAU_2	150	547
area-GS	1148	52
area-GTR_1	1776	2332
area-GTR_2	758	789
area-TNP	2100	924
area-NOM	480	484
Average rotation	*150*	*136*

NF: Normal Forest structure, ***IM***: Ideal management (ha), ***G***: Gini index, ***C***: Carbon balance (10^3 tC), ***VOL***: Harvest volume (10^3 m^3), ***NPV***: Net Present Value (10^3 €). area-BAU_1: area under BAU_1 treatment (ha), area-BAU_2: Area under BAU_2 treatment (ha), area-GS: Area under GS treatment (ha), area-GTR_1: Area under GTR_1 treatment (ha), area-GTR_2: Area under GTR_2 treatment (ha), area-TNP: Area under TNP treatment (ha), area-NOM: Area under NOM treatment (ha). Average rotation (years).

In the auxiliary rows in Table 3, the area selected by the model for each silvicultural alternative is indicated. Also, this solution of the LGP model can be compared with the value proposed by the DM2 (the area pointed out as being the one preferred for applying each silviculture), information which is available on Appendix A (Table A2). In Figure 2 the difference (in surface) between both areas (applied or selected by the model and preferred) can be noted. However, it should be taken into account that the area preferred exceeds the value of the total forest area, because, for each stand, a set of 2–3 possible silvicultural treatments were proposed.

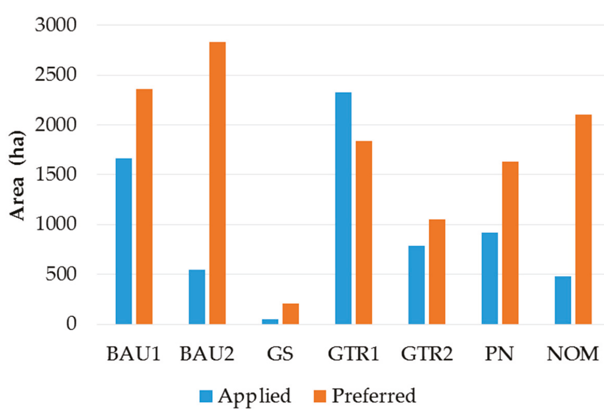


Figure 2. Relation between the silviculture applied in the forest and the deviation of when it would be preferred, according to the categories defined.

5. Discussion

The method here proposed for evaluating sustainability in forest management has the advantage of following the evolution of the criteria over the planning horizon [19], but it could also be adapted when including spatial constraints [97]. In that case, it could be suitable to design a model simultaneously integrating strategic and tactical planning [98]. Furthermore, the methodology proposed could be extended to incorporate the preferences of a group of stakeholders for addressing sustainability [99,100]. Some authors suggest compiling the forest managers' preferences on silvicultural aspects in a goal programming model [101], although the way these individual preferences would be aggregated is still an open question [102]. Finally, although the inclusion of dynamic aspects could trigger highly specific models, limiting their transference to others [103], we do not believe that this could happen in the proposal presented in this study due to its potential adaptation to other works, with other criteria and indicators.

The results presented in Table 3 allow us to observe the differences in relation to the values achieved for the indicators situated at the first priority level, at forest level. Thus, Figure 3 shows how the values of the criteria *NF*, *IM* and *G* obtained in the pay-off matrix are modified (Table 1), with respect to those obtained in the solution of the LGP model (Table 3).

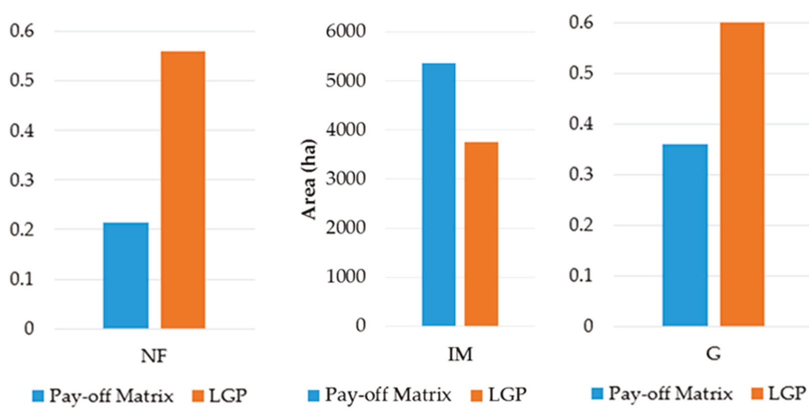


Figure 3. Comparison between the results of the pay-off matrix and those obtained in the LGP model, for the criteria *NF*, *IM* and *G*.

As could be expected, in the comparison between models (Figure 3), the values of the criteria obtained in the LGP model are lower than the ideal ones reached in the pay-off matrix. These reductions indicate the opportunity cost associated with the simultaneous consideration of the six criteria defined in this model, instead of the values proposed in the individual optimization of each criterion. Thus, taking into account that the *NF* and *G* values (located at each end of the graphic) are adimensional and that they represent indicators of the less-the-better type, in the LGP solution their values are 2.7 and 1.6 times worse, respectively, compared to that obtained in the pay-off matrix. Finally, the *IM* criterion's value of 5358 ha, which represents the area managed by the most suitable treatment in each management unit (according to DM2), was reduced to 3750 ha in the LGP solution; i.e., about 30% of the area under ideal management (*IM*) is taken advantage of in LGP, using a different silvicultural treatment from the one that a priori was preferred for application in these areas.

From a sustainability perspective, it has been implicitly assumed up to now that the criteria selected functioned within weak sustainability parameters [31]. Namely, a certain degree of compensation between the different indicators was presumed, although the LGP method implies that there is no finite trade-off between the different indicators of the different criteria considered [89]. However, in the literature, aggregated sustainability indexes based on multicriteria techniques including premises associated with strong sustainability can be found; i.e., it is found that there cannot be compensation between the criteria [104], nor can a certain degree of compensation between criteria even be chosen [105,106].

The methodology proposed here is open to incorporating other silvicultural alternatives. In our case study, GS has been proposed in order to favor the development of multi-aged stands [79], and GTR has been suggested in order to maintain multiple forest values [76], including biodiversity conservation [107], and, especially, to promote silvicultural treatments compatible with the protection of wildlife species [108]. The percentages of mature forest chosen here are those most frequently used in the literature [109,110]. Another silvicultural alternative (TNP) embraces the prohibition of final cuts (this forbiddance is mandatory in all Spanish National Parks). Maintaining this type of protected area is highly beneficial for certain species, and this justifies not employing a conventional silvicultural alternative [111].

On another side, and as mentioned above, other criteria could be integrated into the model, if considered to be appropriate. For example, we are aware that, unlike other studies [112,113], no criterion expressly linked to the social pillar of sustainability has been proposed. Although one study made in the same case study [114] did suggest two recreation indicators, it has not been possible to transfer this idea to our analysis. Along these lines, some studies point to an underrepresentation of social type indicators as being common [103].

Again, and aside from the significance of the Gini coefficient proposed here, which has been applied as an indicator of forest structural heterogeneity [115,116], we have attempted to define our own biodiversity criterion [117] that could be integrated into the LGP model. In fact, one of the objectives in the case study [118] is focussed on the conservation of the black vulture, an umbrella species [119], which is catalogued as "near threatened" at the global level [120]. For this reason, we pursue the possibility that, at the end of the planning horizon, there is a multi-aged forest. The inclusion of this criterion (Gini coefficient) under an environmental pillar is justified when the forest managers aim to promote the existence of uneven-aged stands as a biodiversity conservation measure [63,79].

However, it has not been possible to model the evolution of this species over 100 years, due to the lack of information available for predicting these values, so it has not been included in the analysis. Furthermore, it would have been necessary to determine the impact of the different silvicultural alternatives on the vulture populations, because it has been demonstrated that they have an influence on some requirements of the nesting of this species [121]. The lack of consideration of this criterion illustrates the difficulty in finding criteria compatible with the information assembly over the planning horizon, in spite of the availability of suitable methodologies for their possible integration into the model proposed. However, some studies have been developed under the goal programming technique successfully integrating aspects related to biodiversity [122,123]. Lastly, the methodology proposed here can also be extended, incorporating other silvicultural alternatives centred on other ecosystem services different from timber production [124].

Furthermore, the results of the LGP model permit one to obtain an overall value of sustainability derived from the resolution of that model, making it act as an aggregated index of the sustainability of forest management, assimilating the procedure reported in [125]. Indeed, if the objective is to compare sustainability between similar forests, or between parts of the same one, the solution of the LGP model could allow them to be ranked in terms of greater or lesser aggregate achievement. In [12,13], some examples of this extension are shown. Finally, the opportunity cost in terms of sustainability (gains or losses of sustainability) could also be calculated, by obligating a single silvicultural alternative to be used in some part of the case study. This circumstance can be of interest when, as can be seen in this case, the solutions notably vary with respect to the area that each silvicultural treatment has to cover, and this also happens in other studies [126].

In addition to incorporating new sustainability criteria, one aspect of the methodology proposed here that should be highlighted lies in the combination of flexibility and complexity that can be incorporated, for example, in terms of the silvicultural alternatives considered. The advantage of this flexibility is indispensable for tackling typical contemporary challenges in forest management [127,128]. Since there is no single specific definition of the idea of complexity in silviculture [129], some authors affirm that the impact of certain forest practices on forest system dynamics can compromise their sustainability [81]. Thus, the consideration of diverse silvicultural alternatives for approaching different criteria would lead to what some authors already call "complex adaptive systems" [130]. Lastly, this methodology can be applied at different levels (spatial or temporal) at which it is desired to carry out the planning and silviculture [128], contributing to the flexibility of the proposed methodology.

6. Conclusions

In this study, a flexible methodology was proposed to address sustainability in forest management. It includes the possibility of incorporating different criteria, or even synthetic indicators, multiple silvicultural alternatives for each stand and the preferential weights of different stakeholders. The solutions of these multi-criteria models allow the decision-maker to select, in terms of sustainability, the optimal silvicultural alternative for each stand along the planning horizon, the degree of multi-aged forest proposed and the fulfilment of the normal forest ideal.

The results obtained in the case study show different solutions from the ideal values shown in the pay-off matrix, with those supplied by the LGP model being much more attractive. Moreover, it can be seen how the areas devoted to each silvicultural alternative are notably modified in each of the solutions obtained. Finally, the flexibility of the model leads us to believe that this methodology could easily be extended to other case studies and planning levels, both temporal and spatial.

Author Contributions: M.E. carried out all the research, wrote the manuscript and performed the modelling issues. M.P. wrote the manuscript, focusing on silvicultural alternatives. L.D.-B. coordinated the study and wrote the manuscript, focusing on sustainability topics.

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Appendix A

Table A1. Set of possible silvicultural alternatives to be applied in the case study.

Silvicultural Alternative	Age	Operation	Intensity (%)	Standing Volume (%)
BAU_1	40–60–80	*Light thinnings*	From below	
	120–180	Seeding cutting	50	
		Secondary cutting 1	12	
		Secondary cutting 2	12	
		Final cutting	24	2
BAU_2	40–60–80	*Strong thinnings*	From below	
	120–180	Seeding cutting	50	
		Secondary cutting 1	12	
		Secondary cutting 2	12	
		Final cutting	24	2
GS	40–60–80	*Light thinnings*	From below	
	120–180	Seeding cutting	60	
		Final cutting	35	5
GTR_1	40–60–80	*Light thinnings*	From below	
	80–120	Retention	15	15
	120–180	Seeding cutting	45	
		Secondary cutting 1	10	
		Secondary cutting 2	10	
		Final cutting	18	2
GTR_2	40–60–80	*Strong thinnings*	From below	
	80–120	Retention	30	30
	120–180	Seeding cutting	35	
		Secondary cutting 1	10	
		Secondary cutting 2	10	
		Final cutting	13	2
TNP	40–60–80	*Light thinnings*	From below	
	140–180	Seeding cutting	40	
		Secondary cutting 1	10	
		Secondary cutting 2	10	
		No Final cuttings		40
NOM		NO Management		

BAU_1: Business As Usual 1, **BAU_2**: Business As Usual 2, **GS**: Group Selection, **GTR_1**: Green-Tree Retention1, **GTR_2**: Green-Tree Retention2, **TNP**: Treatment for the National Park, **NOM**: NO Management.

Table A2. Weights for the set of possible silvicultural treatments (7) in each category (7).

Categories	Definition	Set of Alternatives	Weights
1	**Productive stands**	BAU_1 BAU_2 GTR_1	0.188 0.081 0.731
2	**Under protection stands**	NOM TNP	0.9 0.1
3	**Mixed stands**	GS NOM	0.875 0.125
4	**Mixed stands with nests**	GS GTR_1 GTR_2	0.055 0.173 0.772
5	**Mixed stands in the National Park (NP)**	GS TNP NOM	0.149 0.785 0.066
6	**Stands with nests**	GTR_1 GTR_2	0.25 0.75
7	**Stands with nests in the National Park (NP)**	GTR_2 TNP NOM	0.149 0.785 0.066

BAU_1: Business As Usual 1, **BAU_2**: Business As Usual 2, **GS**: Group Selection, **GTR_1**: Green-Tree Retention1, **GTR_2**: Green-Tree Retention2, **TNP**: Treatment for the National Park, **NOM**: NO Management.

Table A3. Scale of relative importance [94].

Intensity of Importance	Definition
1	Equal importance
3	Moderate importance
5	Strong importance
7	Demonstrated importance
9	Extreme importance
2, 4, 6, 8	Intermediate values

Appendix B

Appendix B.1. Lexicographic Goal Programming Formulation

$$LexMin = [U_1, U_2, \ldots, U_V] \tag{A1}$$

being

$$U_1 = \left\{ \sum_{q=1}^{Q} (\alpha_q \cdot n_q + \beta_q \cdot p_q) \right\} \tag{A2}$$

[. . .]

$$U_v = \left\{ \sum_{q}^{Q} (\alpha_q \cdot n_q + \beta_q \cdot p_q) \right\} \tag{A3}$$

subject to:

$$f_q(x) + n_q - p_q = t_q \tag{A4}$$

Starting from v priority levels (Equation (A1)), for each of the priority levels cited, some functions are defined (Equations (A2) and (A3)), composed of the unwanted deviation variables corresponding to the goals (Equation (A4)) situated at those priority levels. t_q is the target level for the qth goal, n_q and p_q are the negative and positive deviations from the target value of the qth goal. $\alpha_q = \frac{w_q}{R_q}$ is used if n_q is unwanted, otherwise is used $\alpha_q = 0$, $\beta_q = \frac{w_q}{R_q}$ if it is unwanted, otherwise $\beta_q = 0$. The parameters w_q and R_q are the weights reflecting preferential and normalising purposes attached to the achievement of the qth goal.

Appendix B.2. Strategic Planning

Following Figure 1A, a strategic forest planning model was designed with a planning horizon of 100 years, divided into 10-year periods, which is a typical timeframe in models with slow-growing species, especially with Scots pine [118]. In short, a timber harvest scheduling model following Model I methodology [121] was built. Initially, Model I requires the definition of the decision variables or prescriptions, which need to encompass all possible management regimes to be considered, taking into account the rotation length and the silvicultural alternatives put into the model, which will remain unaltered throughout the planning horizon [33]. This strategic planning model was fed with the information available in the last forest management plan [82]. In addition, the abovementioned silvicultural alternatives were included in this general model, and we fixed an interval for rotations of between 120 and 180 years. The lowest limit corresponds to the current rotation length for Scots pine in the Sierra de Guadarrama [52], while the upper limit was established at 180 years in order to provide mature forest habitats, which are essential for the survival of several endangered species [84,131]. On the other hand, it is convenient to clarify that, in addition to the endogenous restrictions two exogenous restrictions have been introduced: a minimum harvest area for each silvicultural treatment, and a minimum commercial volume from final cuttings (TNP not included) per period. Finally, considering the rotation length and the 288 stands defined in Valsaín Forest, a set of 11,148 prescriptions was generated.

Appendix B.3. Definition of Model Inputs

Constants

T is the length of the planning horizon.

t is the time period.

$L = T/t$ is the number of periods into which the planning horizon is divided.

ts is the time span that defines the final age class.

$S = T/ts$ is the number of final age classes, taking into account the range of years in which regeneration can occur.

B is the total forest area.

B_i is the area in stand i.

b_{BAU_1} is the minimum harvest area when x_{BAU_1} prescriptions are selected.

b_{BAU_2} is the minimum harvest area when x_{BAU_2} prescriptions are selected.

b_{GS} is the minimum harvest area when x_{GS} prescriptions are selected.

b_{GTR_1} is the minimum harvest area when x_{GTR_1} prescriptions are selected.

b_{GTR_2} is the minimum harvest area when x_{GTR_2} prescriptions are selected.

$H_{\min}$ is the minimum volume harvested per period.

$mAge$ and $MAge$ are the minimum and maximum harvest ages during the planning horizon, respectively.

V_{ijl} is the volume harvested per hectare in stand i, prescription j at period l.

F_z^i is the initial forest inventory on z site index.

BVN is the Black Vulture Nest protection area.

CF_0 is the initial investment and CF_t is the cash-flow per year.

r is the discount rate.

γ is the parameter that expresses the density of wood in tons per m^3 (0.5) and the percentage of carbon content (50%) existing in dry biomass, whose value is obtained through $\gamma = 0.5 \cdot 0.5 = 0.25$ tC/m^3.

Index Sets

i is the number of stands.

j is the number of prescriptions, defining a complete treatment schedule for each stand, following the Model I structure (Johnson and Scheurman, 1977).

k is the number of initial age classes.

l is the index of periods.

z is the site index.

v is the number of priority levels.

Variables

x_{ij} is the area harvested at prescription j in stand i.

x_{BAU_1} is the area harvested by BAU_1 at prescription j in stand i.

x_{BAU_2} is the area harvested by BAU_2 at prescription j in stand i.

x_{GS} is the area harvested by GS at prescription j in stand i.

x_{GTR_1} is the area harvested by GTR_1 at prescription j in stand i.

x_{GTR_2} is the area harvested by GTR_2 at prescription j in stand i.

x_{TNP} is the area harvested by TNP at prescription j in stand i.

x_{NOM} is the area selected for NOM at prescription j in stand i.

ux_i is a binary variable to force decision variable x_i to take either a zero value or a value greater than, or equal to, the minimum harvest area designated by parameters b_{BAU_1}, b_{BAU_2}, b_{GS}, b_{GTR_1} and b_{GTR_2}.

A_s is the area belonging to s final age class s at the ending period.

F_z^f is the ending forest inventory from site index z.

SV_{ij} is the total standing volume at prescription j in stand i.

P is the cumulative percentage of the number of trees per hectare for each stand i.

Q is the cumulative percentage of volume.

CC_{ij} is the carbon capture at prescription j in stand i.

EC_{ij} are the carbon emissions produced by cuttings at prescription j in stand i.

R_q is the normalized vector (as the difference between ideal and anti-ideal values) for each criterion q.

Appendix B.4. Definition of LGP Model

Criteria

NF is the normal forest as an aggregated normalized function of the even flow harvest volume per period (H_l), the forest ending inventory for each site class (F_z) and the area control for each age class (A_s).

IM is the ideal management to be applied in each stand i.

G is the gini index as an inequaluty measure.

VOL is the volume harvested at the end of the planning horizon.

NPV is the Net Present Value at the end of the planning horizon.

C is the carbon balance at the end of the planning horizon.

Achievement function

$$LexMIN = [U_1, U_2, -U_3]$$

$$U_1 = \left\{ w_{NF} \cdot \left(\frac{(p_{NF})}{R_{NF}} \right) + w_{IM} \cdot \left(\frac{(p_{IM})}{R_{IM}} \right) + w_G \cdot \left(\frac{(p_G)}{R_G} \right) \right\}$$

$$U_2 = \left\{ w_{VOL} \cdot \left(\frac{n_{VOL}}{R_{VOL}} \right) + w_{NPV} \cdot \left(\frac{n_{NPV}}{R_{NPV}} \right) + w_C \cdot \left(\frac{n_C}{R_C} \right) \right\}$$

$$U_3 = \left\{ w_{NF} \cdot \left(\frac{(n_{NF})}{R_{NF}} \right) + w_{IM} \cdot \left(\frac{(n_{IM})}{R_{IM}} \right) + w_G \cdot \left(\frac{(n_G)}{R_G} \right) + w_{VOL} \cdot \left(\frac{p_{VOL}}{R_{VOL}} \right) + w_{NPV} \cdot \left(\frac{p_{NPV}}{R_{NPV}} \right) + w_C \cdot \left(\frac{p_C}{R_C} \right) \right\}$$

Goals

(1) **Normal Forest** (*NF*)

$$NF + n_{NF} - p_{NF} = NF*$$

(2) **Ideal Management** (*IM*)

$$IM + n_{IM} - p_{IM} = IM*$$

(3) **Gini index** (*G*)

$$G + n_G - p_G = G*$$

(4) **Carbon balance** (*C*)

$$C + n_C - p_C = C*$$

(5) **Harvest volume** (*VOL*)

$$VOL + n_{VOL} - p_{VOL} = VOL*$$

(6) **Net Present Value** (*NPV*)

$$NPV + n_{NPV} - p_{NPV} = NPV*$$

The following constraints were introduced into the LGP model. First, endogenous ones were introduced to ensure that the area chosen by the model cannot exceed the available area in each stand. Second, a minimum harvest area was proposed for each treatment, since, as the treatments propose cutting sequences at several periods (2–4), a minimum area necessary for the intervention (5 ha for BAU_1 and BAU_2, and 10 ha for GTR_1 and GTR_2) for each of them, was considered. In the case of GS, this minimum area refers to the size of the gaps in which the thinnings are applied. Finally, for TPN and NOM, no amount of minimum area was imposed for their application. The last constraint ensures a minimum harvested volume per period, according to the current forest management plan and the timber harvested in past years.

Subject to:

(7) **Area accounting**

$$\sum_{j=1}^{J} x_{ij} = B_i \ \forall i, j$$

$$x_{ij} = \sum_{j=1}^{J} x_{BAU_1} + x_{BAU_2} + x_{GS} + x_{GTR_1} + x_{GTR_2} + x_{TNP} + x_{NOM} \ \forall i, j$$

$$\sum_{\forall i} B_i = B$$

(8) **Auxiliary variables domain**

$$ux_i \in \{0, 1\}$$

(9) **Minimum harvest area per treatment**

$$x_{BAU_1} - b_{BAU_1} \cdot ux_i \geq 0 \ \forall i, j$$

$$x_{BAU_1} = 0 \ \forall i, j; \ x_{BAU_1} < b_{BAU_1}$$

$$x_{BAU_2} - b_{BAU_2} \cdot ux_i \geq 0 \ \forall i, j$$

$$x_{BAU_2} = 0 \ \forall i, j; \ x_{BAU_2} < b_{BAU_2}$$

$$x_{GS} - b_{GS} \cdot ux_i \geq 0 \ \forall i, j$$

$$x_{GS} = 0 \ \forall i, j; \ x_{GS} < b_{GS}$$

$$x_{GTR_1} - b_{GTR_1} \cdot ux_i \geq 0 \ \forall i, j$$

$$x_{GTR_1} = 0 \ \forall i, j; \ x_{GTR_1} < b_{GTR_1}$$

$$x_{GTR_2} - b_{GTR_2} \cdot ux_i \geq 0 \; \forall i, j$$

$$x_{GTR_2} = 0 \; \forall i, j; \; x_{GTR_2} < b_{GTR_2}$$

(10) **Minimum and maximum harvest age**

$$x_{ij} = 0 \; \forall i, j; \; k < mAge$$

$$x_{ij} = 0 \; \forall i, j; \; k > MAge$$

(11) **Minimum harvested volume per period**

$$H_l \geq H_{\min}, \; l = 1, \ldots, L-1$$

(12) **Non-negativity constraints**

$$x_{ij} \geq 0, \forall i, j$$

$$x_{BAU_2} \geq 0, x_{BAU_2} \geq 0, x_{GS} \geq 0, x_{GTR_1} \geq 0, x_{GTR_2} \geq 0, x_{TNP} \geq 0, x_{NOM} \geq 0$$

$$n_{VOL}, n_{NPV}, n_{NF}, n_{IM}, n_C, n_G \geq 0$$

$$p_{VOL}, p_{NPV}, p_{NF}, p_{IM}, p_C, p_G \geq 0$$

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Article

Weak or Strong Sustainability in Rural Land Use Planning? Assessing Two Case Studies through Multi-Criteria Analysis

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Abstract: This paper addresses the debate regarding weak versus strong sustainability in the field of rural land use planning. Both concepts correspond to opposing paradigms on sustainability and both their fundamentals of economic roots and comparative analyses from a theoretical point of view enjoy a contrasting trajectory. However, their inclusion in land use planning has been an issue not sufficiently studied despite their relevance in the field of local development and sustainability. The aim of this study is to shed light on this gap by exploring the assessment of the degree of sustainability in rural land use planning. To this end, two case studies involving forestry in the Basque Country (Spain) have been analyzed based on a multi-criteria analysis technique. As a result, we have observed the importance of setting thresholds in the valuations of the criteria, as well as the effect of varying such thresholds above the compensability degree.

Keywords: weak sustainability; strong sustainability; multi-criteria analysis; NAIADE; rural land use planning; forestry

1. Introduction

The debate on the definition and scope of sustainability has a long history in terms of measurement and substitutability between different types of capital, with a distinction between strong sustainability and weak sustainability [1]. On the one hand, natural capital represents natural resources, which differs from human-made capital or manufactured capital, which is defined by its capacity for *artificial* reproduction, i.e., its capacity to be reproduced by human beings (e.g., machinery, infrastructures). The compensability and substitutability between natural capital and manufactured capital, the possibility that natural capital can be replaced by manufactured capital, and the effects that such a substitution can generate, have been the origin of the debate on the different degrees of sustainability.

In line with neoclassical economics and in accordance with the pioneering work of Solow [2], and later of Hartwick [3], weak sustainability is circumscribed in the paradigm of substitutability [1]. With the aim of ensuring that human welfare does not decrease, sustainability is defined in terms of the total utility offered by the sum of the accumulated capital—both the natural capital and the manufactured capital—assuming that the latter can replace the former. Sustainability therefore needs to maintain this capital-derived utility over time [4–7]. From this approach, therefore, it is assumed that all the values and functions, both those coming from the natural capital and the manufactured capital, can be quantified using a single scale, generally the monetary one, thus placing it in the framework of strong comparability [8]. Moreover, weak sustainability implies future uncertainty, both in terms of generational preferences and technological capacity [9].

On the other hand, strong sustainability argues that many of the values and services offered by nature cannot be replaced by human-made capital. This approach developed by ecological economics [10] argues that certain natural resources are limited and irreplaceable and therefore a minimum amount of different types of capital must be conserved [11–13]. In line with this, Pelenc and Ballet [14] argue that the natural capital has at least four characteristics that differentiate it from the manufactured capital: (i) the irreversibility of the natural capital [15]; (ii) natural capital is multifunctional, so it is unlikely that manufactured capital will act as an appropriate substitute for it; (iii) the lack of knowledge about the effects of the destruction of the natural capital, so it is appropriate to consider a precautionary principle; and (iv) ethical and justice issues with respect to future generations since an increase in future consumption is not an appropriate substitute for loss of natural capital. From this perspective, natural capital is neither compensable nor replaceable by manufactured capital, at least not in its entirety, and therefore cannot be perceived as a *stock* of resources. The fact that they are irreplaceable, places strong sustainability in the context of incomparability or weak comparability [8]. In addition, the existence of critical natural capital requires the setting of minimum conservation limits in the natural capital [15,16]. The critical threshold of a natural resource marks the level at which it loses its resilience, and falls into a position of irreversibility [17–19]. According to this principle, a certain amount of natural capital must be secured if the functions it offers to human welfare are to be maintained.

Recently, research in several areas has taken up the debate on strong sustainability and weak sustainability with a more practical vision: fisheries management [20]; urban heritage [21]; choice of technologies [22]; restoration of contaminated land [23]; public infrastructure [24]. However, spatial planning and land use planning are still insufficiently studied issues. In this respect, we must bear in mind that rural land is a limited and irreplaceable natural resource, and that under current conditions, it is difficult for the various functions and values it offers for human well-being to be replaced or even offered by technological advances. In view of this, land use planning should therefore consider the different values offered by rural soil ecosystems, together with the values coming from the socio-economic activities developed on that soil, and establish, if necessary, an acceptable degree of compensability.

So, the aim of this study is to shed light on this gap by: (i) approaching the conceptual framework for debate on the integration of sustainability in rural land use planning; and by (ii) exploring the assessment of the degree of sustainability in such a context. To this end, two case studies have been analyzed, applying a sustainability assessment tool based on a multi-criteria analysis technique. We have been able to analyze the issue of trade-offs among different dimensions of rural land use planning. With this aim, the paper is structured as follows. The next section addresses the issue of sustainability in rural land use planning. The third section describes the two case studies, and the methods and criteria employed for the analysis. In Section 4, we undertake the sustainability analysis and the results, and in Section 5, discussion is approached. Finally, in Section 6, we present the main conclusions drawn from the analysis of sustainability in rural land use planning.

2. Integrating Sustainability in Rural Land Use Planning

Sustainability is an issue that is intrinsically linked to land planning as a discipline that is approached under a systemic vision, as the territorial model is influenced by, among others, the physical environment and land uses, human settlements, and governance [25]. Planning strategies are also influenced by the different levels, hierarchies, principles, and scales in dispute [26], and for decisions to be sustainable, they must be based on multidimensional and multiscale analyses, assessment methods must be comprehensive and also include participatory processes [27]. In fact, given its multidimensional and multiscale nature, the integration of sustainability in land planning has been analyzed from multiple perspectives, such as: territorial plans that combine the socio-economic benefits with the environmental costs of regional growth [28]; the application of sustainability principles in the strategic environmental assessment of urban planning [29]; and the relationship between agricultural multifunctionality and sustainability in the framework of urban land uses [30].

In this multidimensional framework, however, rural land use planning has some particularities to take into account. First, the rural land and its main uses, agriculture and forestry, provide diverse values and functions for human well-being, such as the provision of food and raw materials, the maintenance of ecosystems, and the protection of species and water [31,32]. In the last few decades, land uses have changed widely in Europe [33]. These changes have affected natural land ecosystems, and the increasing urbanization of rural areas, intensive agriculture and forestry, and the abandonment of traditional land uses have had a significant impact on the landscape and biodiversity [34,35]. The increasing consumption of energy, water, and soil nutrients and the increase in plantations of exotic species are degrading soils and reducing biodiversity. This accelerates the natural processes of change and affects the provision of ecosystems goods and services to society [28,36–40].

Secondly, different change processes are taking place at the same time in rural land uses influencing each other [35]. Land science, as well as agricultural and forestry sciences, have spent considerable effort measuring, monitoring, and modeling such patterns [41–44]. Thus, the challenge is how to define and determine sustainable rural land use planning, i.e., how to integrate it comprehensively within socio-ecological systems where maintenance of both socio-economic activities and ecosystem services are pursued. From this multidimensional perspective, the question focuses on how to compare these different dimensions, and how to establish the possible compensations between them, if that is the case. For this purpose, the trade-offs between socio-economic benefits and environmental values must be considered [28,45]. The balance between those dimensions may determine the sustainability of the model, opening the debate about compensability and substitutability that can be allowed between different dimensions. These arguments lie on the basis of the distinction between strong sustainability and weak sustainability.

Last but not least, as noted, sustainable land use planning therefore requires multidimensional and multidisciplinary methods that can work with an integrating vision, whereby multiple disciplines work simultaneously [46]. In this sense, multi-criteria decision aid (MCDA) has emerged as an adequate support tool for decision-making on environmental management problems [8,47–49]. The multi-criteria analysis considers multiple dimensions of environmental issues, works with quantitative and qualitative information, considers the uncertainty in the future [50], and the complexity of environmental decisions [8]. Furthermore, by applying compensatory and non-compensatory multi-criteria analysis techniques, it is possible to evaluate various options and to identify trade-offs between different criteria [51]. Additionally, participatory multi-criteria methods have demonstrated their usefulness and applicability in land use planning [28,46,52–54].

3. Case Studies and Methodology

3.1. Case Studies: Contetxt and Methods

Two previously published case studies on rural land use planning have been used as references for this analysis. Both were carried out in the province of Gipuzkoa in the Basque Country (Spain), where forest policy in recent years has been the subject of debate between productivist positions and ecological visions. The first study was carried out in a Special Area of Conservation (SAC) integrated into the Natura 2000 Network (N2000), called Garate-Santa Barbara [55]. The second was held around the rural land of the municipality of Mutriku [56]. In both evaluations, the social multi-criteria evaluation (SMCE) methodological framework and the Novel Approach to Imprecise Assessment and Decision Environments (NAIADE) aggregation method were used, facilitating and giving robustness to the comparison between both cases.

The SMCE is a tool to help decision-making in complex socio-ecological contexts [48,57]. Complex socio-ecological systems usually present immeasurable values and uncertainty, affecting heterogeneous groups of stakeholders with different interests, often in opposition to each other [8,58,59]. The SMCE is characterized by a multidisciplinary and participatory approach aimed at facilitating the search for solutions in natural resource management and sustainability, such as land use planning and territorial management [46,52]. (For an exhaustive review of both the methodological foundations of the SMCE and its applications, we recommend reviewing Munda [48,57], as well as the case studies analyzed).

Within MCDA framework, NAIADE belongs to the wide range family of outranking methods [60]. It was initially devised by Munda [61], and then technically developed [62]. It has been subsequently undertaken in multiple cases as support for decision-making, as for example, in forest planning (For further details, see Acosta and Corral [63]). Operationally, NAIADE makes comparisons of alternatives in pairs and, applying a mathematical algorithm, ranks the alternatives from the most suitable to the least suitable [62]. It simultaneously accepts criteria evaluated in different units of measurement, both quantitative and qualitative, this being a fundamental characteristic for carrying out multidimensional evaluations. NAIADE also allows a conflict analysis to be carried out by means of the degree of preference or rejection that the social actors involved have with regard to the different alternatives. Finally, NAIADE allows the model to introduce variations in the aggregation conditions in order to observe the effect of these variations on the final result.

3.1.1. Case Study 1: Garate-Santa Barbara (GSB)

GSB is a protected area in Gipuzkoa of approximately 142 hectares, which in 2003, was proposed to become part of the N2000, and since 2013, is an SAC of the aforementioned network. The reasons for this inclusion are the high value of native forest species found in the area, in particular, the cork oak (*Quercus suber*). In turn, GSB is valued as a recreational area because of its landscape made up of small farms and forests. However, in recent decades, the wine industry, dedicated to the production of a variety of white wine, *txakoli*, has grown significantly, becoming the main economic activity in the area. This has meant a change in land use, with more and more land being devoted to the cultivation of vineyards. The expansion of vineyards has led to a conflict between the defenders of native forests and the landowners, whose aim is to make the land profitable by growing vines for the production of *txakoli*. In recent years, there has been an increasing number of conflicts over different land uses within the N2000 [64], which shows the relevance of this case study.

The study by Etxano et al. [55] assesses different land uses, proposing scenarios in which the areas dedicated to vineyards and native forest vary. Different land use alternatives were defined according to the intensity of ecological value enhancement, also considering a system of additional payments in each of the possible scenarios (The payment system contemplates: (i) the compensations established by the provincial government for the reforestation with slow-growing tree species in N2000 areas, scenarios A21, A31, and A41; and (ii) additional compensation for lost profits and/or increased social welfare derived from the improvement of landscape characteristics and biodiversity, scenarios A22, A32, and A42). Table 1 shows the scenarios and land uses for each of them.

Table 1. GSB land uses by scenario (in ha and as a % of total).

	Scenario 0	**Scenario 1**	**Scenario 2**		**Scenario 3**		**Scenario 4**	
	Status Quo (%)	**Business As Usual (%)**	**Ecological Values Strength Moderate (%)**		**Ecological Values Strength High (%)**		**Ecological Values Strength Maximum (%)**	
Alternatives	A01	A11	A21	A22	A31	A32	A41	A42
Cork oak	16.6 (11.6)	16.6 (11.6)	21.1 (14.7)		28.3 (19.8)		51.7 (36.1)	
Indigenous Woodland	18.7 (13.1)	18.7 (13.1)	21.6 (15.1)		24.4 (17.0)		41.8 (29.2)	
Heather land	24.5 (17.1)	24.5 (17.1)	24.5 (17.1)		26.5 (18.5)		3.0 (2.1)	
Forest plantation	22.9 (16.0)	21.3 (14.9)	15.5 (10.8)		3.5 (2.5)		0.0 (0.0)	
Pasture, allotments and crops	44.4 (31.0)	42.1 (29.4)	44.4 (31.0)		44.4 (31.0)		34.1 (23.8)	
Vineyard	16.1 (11.2)	19.9 (13.9)	16.1 (11.2)		16.1 (11.2)		12.6 (8.8)	

Source: adapted from [55]. Note: Scenarios 2, 3, and 4 foresee a certain land use distribution (a certain area value and percentage) regardless of the compensation system.

The multi-criteria impact matrix shows the assessment obtained by each alternative for each of the different evaluation criteria (Table 2).

Table 2. Impact matrix for the case of GSB.

Criteria	**Unit**	**Alternatives**							
		Status Quo	**Business As Usual**	**Ecological Values Strength Moderate**		**Ecological Values Strength High**		**Ecological Values Strength Maximum**	
		A01	**A11**	**A21**	**A22**	**A31**	**A32**	**A41**	**A42**
Landscape	Index	10,527	10,590	11,092	11,092	11,928	11,928	15,073	15,073
Biodiversity	Index	199	200	218	218	247	247	345	345
Recreation and cultural value	Million €	0	0	3.51	3.51	3.51	3.51	0	0
Social well-being	Million €	0	1.13	17.34	17.34	30.19	30.19	145.44	145.44
Cost	€	0	0	3583	29,361	9389	36,328	11,106	67,671
Income generation	€	115,838	134,616	118,222	144,000	121,936	148,875	98,547	155,111
Agricultural activity	ordinal	5	6	4	2	3	1	5	4
Acceptability	ordinal	5	6	3	2	4	1	5	3

Source: [55].

Based on the impact matrix, NAIADE calculates the different degrees of preference (index $\phi+$) and the degrees of rejection (index $\phi+$) (see Figure A1 in Appendix A). The index $\phi+$reflects the ranking based on the number of criteria in favor of each alternative, and the index ϕ-reflects the ranking based on the number of criteria against each alternative. The intersection between both indexes (the third column, Figure A1 in Appendix A), shows the ranking of alternatives from most to least suitable with respect to the assessment criteria used [62].

In this case, the best ranked alternative is A32 ("F" in Figure A1 in Appendix A), an alternative that offers high ecological values, combined with additional compensations (see "Intersection" in the third column of Figure A1 in Appendix A). In this alternative, the areas devoted to cork oak and indigenous woodland are significantly increased and those devoted to forest plantations are reduced. In the second position in the ranking is the alternative A42("H"), which proposes a maximum ecological value enhancement through a greater surface area of cork oak and native forests and a reduction of the land destined to forest plantations and agricultural uses, also combined with additional compensations.

3.1.2. Case Study 2: Mutriku Municipality

In the context of the elaboration of the Municipal Land-Use Plan of Mutriku, Etxano et al. [56] evaluated different alternatives of rural land use planning. Mutriku is a coastal municipality of Gipuzkoa, covering approximately 2700 hectares, where the Arno massif stands out, a SAC of the N2000 due to the great value of the Atlantic holm oak (*Quercus ilex*), which abounds. Due to its particular location, this municipality did not have the important industrial development of other municipalities in the area, maintaining until the mid-twentieth century an important agricultural activity and the traditional landscape of the rural mid-mountain areas of the Basque Country. However, in recent decades the relatively nearby industrial areas have led to the abandonment of agricultural activity, reducing the area of cultivated land and increasing the area occupied by coniferous forests to a large extent. This change in rural land use has meant a major change in the landscape, economy, and culture of the rural environment, as in many other locations on the Cantabrian coast [65].

Given the changes in rural land use in recent decades, three possible scenarios for the future were outlined: continuing with the current dynamics, promoting new agricultural activities, and promoting forests of native species. These scenarios are developed in five specific alternatives, showing different land uses for each (Scenario A1 would be continue with the current dynamics. The second scenario proposes a medium (A2a) or maximum (A2b) potentiation of agricultural activity, and conifer-based forestry policy and is divided into two alternatives that propose the medium potentiation (A3a) of forests of native species and the maximum potentiation (A3b) of this new forestry policy). Table 3 lists the areas of the different land uses for each alternative.

Table 3. Scenarios and rural land uses for Mutriku (in ha and as a % of total).

Scenarios	**Scenario 1**	**Scenario 2**		**Scenario 3**	
Alternatives	**A1**	**A2a**	**A2b**	**A3a**	**A3b**
Mixed Atlantic woodland	290.26 (10.7)	290.26 (10.7)	290.26 (10.7)	590.16 (21.7)	667.96 (24.5)
Holm oak woodland	459.64 (16.9)	459.64 (16.9)	459.64 (16.9)	459.64 (16.9)	459.64 (16.9)
Forest plantation	1176.60 (43.2)	1176.60 (43.2)	1156.60 (42.5)	876.7 (32.2)	798.9 (29.4)
Pasture and scrubland	191.75 (7.0)	139.85 (5.1)	139.85 (5.1)	139.85 (5.1)	139.85 (5.1)
Meadows and farmland	524.51 (19.3)	576.41 (21.2)	596.41 (21.9)	576.41 (21.2)	576.41 (21.2)
Urban land	77.71 (2.9)	77.71 (2.9)	77.71 (2.9)	77.71 (2.9)	77.71 (2.9)
Total	2720.47 (100.0)	2720.47 (100.0)	2720.47 (100.0)	2720.47 (100.0)	2720.47 (100.0)

Source: adapted from [55].

On the other hand, Table 4 shows the impact matrix of the case studied, where the assessment received by each alternative in each of the different criteria is shown.

Table 4. Impact matrix for the case of Mutriku.

Dimensions	**Criteria**	**Unit of Measurement**	**Trend**	**Alternatives**				
				Business As Usual	**Promote New Agricultural Activities**		**Promote Native Species Forests**	
				A1	**A 2a**	**A 2b**	**A 3a**	**A 3b**
Ecological	Biodiversity	Index	Max	245,383	246,732	247,992	268,025	273,549
	Landscape	Index	Max	3,387,206	3,392,183	3,397,733	3,774,555	3,873,750
Economic	Agricultural income	€	Max	367,028€	459,295€	461,120€	440,515€	435,643€
	Public cost	€	Min	379,429€	416,259€	426,565€	561,801€	599,444€
Social	Local consumption	Qualitative	Max	Quite bad	Quite good	Good	Quite good	Quite good
	Attachment to the land	Qualitative	Max	Average	Good	Good	Bad	Bad

Source: [56].

The results of the assessment carried out in the case of Mutriku show that the best ranked alternatives according to the criteria used are A2b ("C" in Figure A2 in Appendix A) and A3b ("E"), while the worst ranked alternative is A1 ("A"). Among the first ones (A2b and A3b), it is not possible to say that one of the two alternatives is more favorable than the other, they are incomparable between each other since they show the same degree of suitability. Technically, incomparability is a particular case arising from the intersection between the pre-ordering of degrees of preference (column $\phi+$in Figure A2 in Appendix A) and degrees of rejection (column ϕ-) [47,62]. This incomparability lies in the fact that, while sharing certain requirements for consideration in the assessment, the two alternatives have characteristics of a different nature.

In addition, the social evaluation carried out in this case shows that, among the most technically adequate alternatives, the A3b is preferred by a wide number of actors, a group that comprises the most environmentalist positions of the public administrations, the technicians working in rural development, as well as the different social groups and associations. However, it is the least valued alternative for another group of actors, the one formed by the landowners, the traditional farmers, and the traditional positions of the provincial public administration. A3b, being one of the most technically suitable alternatives, presents a high degree of social conflict due to the conflicting opinions that exist in society regarding forest policy.

3.2. Methodology

Upon those case studies, an analysis of different degrees of sustainability has been carried out. Parameters of the model have been modified, affecting the compensability and substitutability of the valuations in the different criteria, with the aim of placing the model before the paradigms of strong sustainability or weak sustainability. Three types of modifications have been introduced in NAIADE to observe its behavior: (i) on the degree of compensation between criteria (parameter γ); (ii) on the credibility index (parameter α); (iii) on the thresholds of preference and indifference between criteria scores. In addition, (iv), a trade-off analysis has also been carried out through NAIADE by comparing alternatives by criteria. The first two analyses have been carried out jointly to facilitate understanding. The modification of the parameters γ and α has been a recurrent technique for sensitivity analysis in numerous empirical works [66–71].

(i) Variations in the compensation index (parameter γ) and the credibility index (parameter α)

The parameter γ establishes the level of compensation between valuations obtained by the same alternative on different criteria [62]. Compensation means that positive valuation obtained on certain criteria can be offset by negative valuation on other criteria. This parameter obtains values between 0 and 1. A low value of γ allows the compensation between valuations, placing the model in the framework of the weak sustainability. Conversely, a high value of γ indicates that the valuations do not offset each other, placing the model in the strong sustainability framework.

On the other hand, the parameter α reflects the uncertainty of the model. The parameter α increases or relaxes the minimum difference required for the criteria assessments to be considered in the aggregation process, i.e., it establishes a greater or lesser intensity of preference or distance between assessments [62]. This parameter affects all criteria simultaneously, relaxing or tightening the intensities of preference.

(ii) Variations in preference and indifference thresholds

Variation of preference and indifference thresholds is another method for testing model robustness [70–72]. The thresholds are set for each criterion, and they mark the minimum differences between valuations for an alternative to be ranked in different positions of suitability, that is, they set the differences in valuations that an alternative must obtain in a criterion in order to be considered much better, better, equal, worse, or much worse than another. The thresholds for the qualitative criteria are set by default in the NAIADE aggregation process. The thresholds of the quantitative criteria, however, are fixed through the technical work of the analysts, and must reflect the positions shown by the social actors in the participatory process, this being one of the most delicate aspects of the evaluation, because of the subjectivity and responsibility that it entails [73]. To minimize this subjectivity, authors such as Vallejo et al. [71] define the thresholds based on the maximum and minimum values obtained by the alternatives for each criterion. Otherwise, the thresholds are reduced or increased by 50% to observe the effect of these variations on the results [70].

(iii) Trade-off analysis

As a complement to the previous analyses, the best ranked alternatives in each case study have been compared with respect to the evaluation criteria. This analysis allows us to observe the differences between the alternatives with respect to each criterion, which makes it possible to know in each alternative the valuations by criteria in terms of trade-off. This analysis is interesting in terms of sustainability in that if the criteria are perceived as *proxy* of the various types of capital, i.e., natural capital vs. manufactured capital, it shows the potential trade-offs or substitutability between them.

4. Analysis and Results

4.1. Sustainability Analysis of Case Study 1: GSB

(i) Variations of the parameter γ and of the parameter α

For this analysis, the model was first tested giving different values to γ. According to the objective pursued, the parameter has been varied from $\gamma = 0.1$ (alignment with weak sustainability) to $\gamma = 0.9$ (alignment with strong sustainability), keeping constant $\alpha = 0.5$. It can be seen that the result does not vary significantly with these variations, so the greater or lesser degree of compensation does not have a determining influence (see Table A1 in Appendix B).

On the other hand, it has also been verified that, given the values of the credibility index of $\alpha = 0.3$, $\alpha = 0.5$, and $\alpha = 0.7$, the result does not vary significantly and, alternatively, A32 remains first in the ranking (Table A1 in Appendix B). For any value of γ, if we reduce the minimum difference between scores required to consider different two alternatives, that is, when we reduce to $\alpha = 0.3$, the intersection shows that alternative A32 is still more suitable. However, if α increases to $\alpha = 0.7$, the minimum differences required between valuations to consider two different alternatives are relaxed by cancelling the effect of the small differences, and in this case, the model places several alternatives, A42, A32, A31, and A22 in the first place of the ranking, not being able to establish a preference between them. In terms of natural capital, A42 is the most valuable alternative, followed by A32 and A31, and lastly A22.

(ii) Variations in preference and indifference thresholds

Based on the preference thresholds established in the case study (Table 5), this analysis has proceeded in two directions. Firstly, the thresholds initially established have been extended by 30%, requiring greater differences in order to consider the assessments of the alternatives differently, and secondly, the thresholds have been reduced by 30% in accordance with the reduction proposed by Vallejo et al. [71]. By reducing the thresholds, the result does not change, and the best rated alternative remains A32 followed by A42. However, if we increase the thresholds, the best rated alternative remains A32 but A42, A32, and A22 are placed in second place, coinciding with what was obtained by setting $\alpha = 0.7$.

Table 5. Criteria preference thresholds for GSB.

Criterion	Indicator	Preference Thresholds			
		Much Better (≥); Much Worse (≤)	Better (>); Worse (<)	Almost the Same (~=)	Same (=)
Landscape	Index	3000	2000	1000	100
Biodiversity	Index	40	30	10	0
Recreational value	Million €	2	1	0.5	0
Social welfare	Million €	140	100	50	0
Public cost	€	10,000	6000	3000	0
Income generation	€	10,000	7000	4000	2000
Agricultural activity	Qualitative	≥; ≤ 0.375	>; < 0.6	~= 0.32	= 0.0
Acceptance	Qualitative	≥; ≤ 0.375	>; < 0.6	~= 0.32	= 0.0

Source: adapted from [55].

Finally, for a more complete analysis, the thresholds of the ecological criteria, i.e., landscape and biodiversity, have been reduced. The aim is to observe the effect on the result of any minimal variation in the valuation of these criteria. By reducing the preference thresholds of these criteria by 50%, we achieve a greater effect of any minimum difference in their valuations, and therefore, their final effect on the result increases. Given these variations, the ranking of alternatives does not vary significantly in this case, with the best ranked alternative being A32, and the second A42.

(iii) Trade-off analysis

In the two best evaluated alternatives (A32 and A42), a change in land use is proposed, increasing the areas dedicated to different native species to the detriment of forest plantations. Additional aid to that currently approved for the promotion of these native species is also envisaged. If these two alternatives are compared, it can be seen that alternative A32, the best rated, obtains better ratings in the criteria of recreational and cultural value, cost, agricultural activity, and social acceptance, while A42, however, obtains better ratings in landscape, biodiversity, and social welfare (Figure A3 in Appendix A), being consistent with the greater presence of natural capital in this last alternative.

4.2. Sustainability Analysis of Case Study 2: Mutriku Municipality

(i) Variations of the parameter γ and of the parameter α

In the event of variations in the compensation index $\gamma = 0.1$, $\gamma = 0.5$, and $\gamma = 0.9$, and keeping constant $\alpha = 0.5$, neither the rankings of the alternatives nor their intersection varies significantly, and alternatives A2b and A3b remain the most suitable (Table A2 in Appendix B). Therefore, the degree of compensation is not decisive in the final result, and therefore no alignment with respect to weak/strong sustainability is observed. Similarly, the behavior of the model is observed by giving different values to the parameter α (Table A2 in Appendix B), seeing that the result does not vary significantly, with alternatives A2b and A3b being the first in the ranking.

On the other hand, for any value of γ, when the minimum difference between valuations required to consider different two alternatives is relaxed, that is, when less differences are considered sufficient ($\alpha = 0.3$), the intersection shows that alternative A3b, the one with the highest ecological value by means of maximum potentiation of native forests (high natural capital), is shown to be the most appropriate. On the contrary, if α increases ($\alpha = 0.7$) and the minimum differences are no longer a determining factor in the final ranking, the intersection shows that alternative A2b, which proposes a more humanized rural environment through maximum agricultural empowerment, i.e., with fewer natural capital than A3b, is the most appropriate.

(ii) Variations in preference and indifference thresholds

From the preference thresholds defined in this case (Table 6), as in the previous case, we have proceeded in two directions. On the one hand, the preference thresholds have been increased by 30% and, on the other, they have been reduced by 30% as proposed by Vallejo et al. [71] in order to observe the effect of these variations on the result.

Table 6. Criteria preference thresholds in the case of Mutriku.

		Preference Thresholds			
Criterion	**Indicator**	**Much Better (≥); Much Worse (≤)**	**Better (>); Worse (<)**	**Almost the Same (~=)**	**Same (=)**
Biodiversity	Index	8000	5000	4000	1000
Landscape	Index	10,000	6000	4000	400
Profitability	€	40,000	25,000	15,000	1000
Public cost	€	70,000	50,000	25,000	5000
Local consumption	Qualitative	≥; ≤ 0.375	>; < 0.6	~= 0.32	= 0.0
Attachment to the land	Qualitative	≥; ≤ 0.375	>; < 0.6	~= 0.32	= 0.0

Source: adapted from [55].

When faced with threshold extensions, alternative A2b is shown to be the most appropriate in most cases. This result coincides with the one obtained when modifying $\alpha = 0.7$ (keeping the preference thresholds unchanged). When faced with reductions in the thresholds, the results obtained indicate that alternative A3b is the most suitable, and alternatives A2a, A2b, and A3a are in second place. That is, by reducing the difference requirement for considering different alternatives, the A3b alternative is the most suitable. This result coincides with that obtained by lowering the credibility index to $\alpha = 0.3$ (keeping the preference thresholds unchanged).

Finally, as in the previous case study, the preference thresholds of the criteria reflecting the ecological dimension, biodiversity and landscape have been modified, reducing them by 50% (keeping the preference thresholds of the other criteria constant). In this way, any minimal variation in the valuation of these criteria is considered relevant, and takes on greater weight in the result. In this case, it can be seen that the A3b alternative, the one with the highest ecological value, appears better positioned in the final ranking of alternatives.

(iii) Trade-off analysis

If we compare alternatives A2b and A3b by criteria, we see that certain criteria act as trade-offs in the opposite direction in each of them (Figure A4 in Appendix A). The A2b alternative, which proposes the maximum potentiation of new agricultural models while maintaining the current forestry policy, obtains better valuations in the criteria of attachment to the rural land and public cost, and much worse valuations in biodiversity and landscape, respectively. At the same time, the A3b alternative, which proposes a change in forestry policy towards the promotion of native species to the detriment of forest plantations, obtains better evaluations in the criteria of biodiversity and landscape, and worse in attachment to the rural land and public cost, due to the aid proposed for the change in the forestry model.

4.3. Overall Results

From the analyses made and their relationship with the degree of sustainability, we obtain the following results.

Firstly, with regard to variations of the parameter γ and keeping $\alpha = 0.5$, the result remains unchanged in both cases. In the first case, alternative A32 is the best valued, followed by A42. In the case of Mutriku, the A2b and A3b alternatives are the most suitable, although they are incomparable. This means that the variations of γ, i.e., the degree of substitutability does not influence the result.

Therefore, the compensation index does not determine the alignment of the case studies models with respect to weak/strong sustainability. Secondly, given the simultaneous variations of γ and α, we conclude that the determining parameter is α and not so much γ. In fact, for any value of γ and if it increases α, in the case of GSB, four of the alternatives assessed, A22, A31, A32, and A42, occupy the first place in the ranking, and in the case of Mutriku, alternative A2b is presented as the most suitable. Thirdly, it should be noted that these same results coincide with those achieved in the case of GSB in the face of variations in the preference thresholds. In the case of Mutriku, when increasing the thresholds, the most suitable alternative is A2b, i.e., the same result as when increasing α. Similarly, lowering preference thresholds, the A3b is the most suitable alternative, i.e., the same result as lowering α.

A high value of α, therefore, means an increase in the preference thresholds, the model is more insensitive to small differences between the valuations, and fewer criteria are considered in the aggregation process. Similarly, with the reduction of α, small differences in the valuations have a decisive effect on the outcome of the model, and a greater number of criteria are considered in the aggregation process. In the case of GSB, when α increases, four alternatives are at the top of the ranking, all of which advocate different intensities of ecological value enhancement. In the case of Mutriku, in view of an increase in α, the A2b alternative, which obtains better ratings in the economic and social dimensions, emerges as the best valued. This result could be aligned with the weak sustainability paradigm, given that the best valuations of alternatives that propose greater manufactured capital could hypothetically compensate for natural capital decreases. On the other hand, when α is reduced, it may be the case of an enhancement of natural capital as: in GSB, the best ranked is A32, an alternative that poses a high ecological value (high natural capital), and in Mutriku, the best ranked is A3b, an alternative that poses a higher natural capital than A2b.

5. Discussion

The sustainability analyses carried out in this study allow us to go deeper into the degree of sustainability achieved, or even determine the conditions assumed either by strong sustainability and weak sustainability paradigms.

The general approach to address weak/strong sustainability issue has traditionally focused on substitutability and compensability, and it has been the case in diverse applications (see [1]). Particularly within MCDA context, the use of compensatory and non-compensatory methods has also been deeply discussed in terms of outcomes achieved [51,60], and they have been respectively linked to weak and strong sustainability paradigms [23,24]. By means of the two case studies, we have tried to go further, adding to the analysis the performance of the model when varying particular parameters beyond compensability (credibility index, preference, and indifference thresholds), and comparing alternatives in a trade-off view.

From the results of our analysis, it can be deduced that in addition to the general approach to address strong and weak sustainability according to the degree of compensation between natural capital and manufactured capital, the setting of preference thresholds and the number of preference relations considered can also be considered as determining factors. In other words, the sensitivity of the model to small differences between valuations and the inclusion of all criteria are key to determine weak and strong sustainability approaches. In this regard, on the one hand, some authors do not link the credibility index (parameter α) with sustainability, but only with the uncertainty of the model, since it influences the intensity of preference [66,67]. On the other hand, Shmelev and Rodríguez-Labajos [68] interpret a high α as strong sustainability to the extent that a lower degree of compensation among criteria is allowed, and vice versa. However, the variations in α do affect the defined preference thresholds, relaxing the model by considering only criteria where there are large differences between alternatives (increase in α) or making it stricter (decrease in α), but they act on all the criteria simultaneously without knowing exactly their effect on each of them. Therefore, the variations in the preference thresholds of each criterion allow us to face the sustainability analysis with greater guarantees.

In both case studies, the lower value we give to α or the lower preference thresholds we establish, i.e., the more sensitive the model is to small differences between valuations, the best ranked alternatives are that propose high natural capital. Similarly, the higher values of α or wider preference thresholds, alternatives with high manufactured capital are in the top positions of the ranking. Therefore, the more sensitive or strict in terms of small differences the models are, the larger the natural capital alternatives are projected to be, i.e., the alternatives that propose an increase in the area of native forests and a reduction in forest plantations. These alternatives, in turn, would be in a position to provide greater ecological values and ecosystem services. Thus, these results would be aligned with strong sustainability, all the more so as this natural capital would not be replaced by the manufactured capital in the future. It is reasonable to think that the natural capital will not be replaced in protected areas such as N2000; in particular, GSB is included in N2000, and an important part of Mutriku municipality is so.

Additionally, the definition of critical thresholds of diverse dimensions is also a key prerequisite to approach strong sustainability [20,21]. In fact, in our analysis, the establishment of the critical natural capital threshold is an underlying issue. For example, in the case of Mutriku, the reduction of the preference thresholds of the ecological criteria (i.e., biodiversity and landscape), which gives greater importance to minimal differences in the valuations of these criteria, makes the effect of these criteria on the result greater, increasing their weight in the result. In fact, if we reduce the thresholds of the biodiversity and landscape criteria while keeping the thresholds of the other criteria constant, alternative A3b, the one with the highest ecological value, is better positioned in the overall ranking. This highlights the possibility of establishing critical natural capital thresholds for the criteria that reflect the ecological dimension, which, however, should be established for each specific case given the multiple complex interrelations that exist in socio-ecological systems.

6. Conclusions

A procedure has been developed to assess the response of multi-criteria models to the strong and weak sustainability paradigms by performing a sustainability analysis. The development of this analysis in the two case studies has, in turn, highlighted the validity and possibilities offered by the NAIADE aggregation method for such analysis. In addition, to our knowledge, there is no application of SMCE that addresses the weak vs. strong sustainability issue in depth, so this analysis carried out on two case studies aims to contribute to this debate, both methodologically and conceptually.

The analysis has shown that sustainability in rural land use planning is a concept that goes beyond the possible trade-off between different types of capital. On the one hand, the analysis carried out has shown that the substitutability or non-substitutability of different types of capital is not the only issue that determines the degree of sustainability of a model. On the other hand, from the sustainability analysis, it can be deduced that the establishment of the credibility index (α), the thresholds, and the preference intensities are factors that determine the sensitivity of the model to small variations and the inclusion or not of all the criteria, influencing the alignment of the models within the framework of the strong sustainability or weak sustainability. However, the variations on α act on all criteria simultaneously without the exact effect on each of them being known. For this reason, the variations of the preference thresholds offer a greater guarantee for the sustainability analysis, providing insight about the exact effect of the variations of the preference thresholds of each criterion on the final result.

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Appendix A

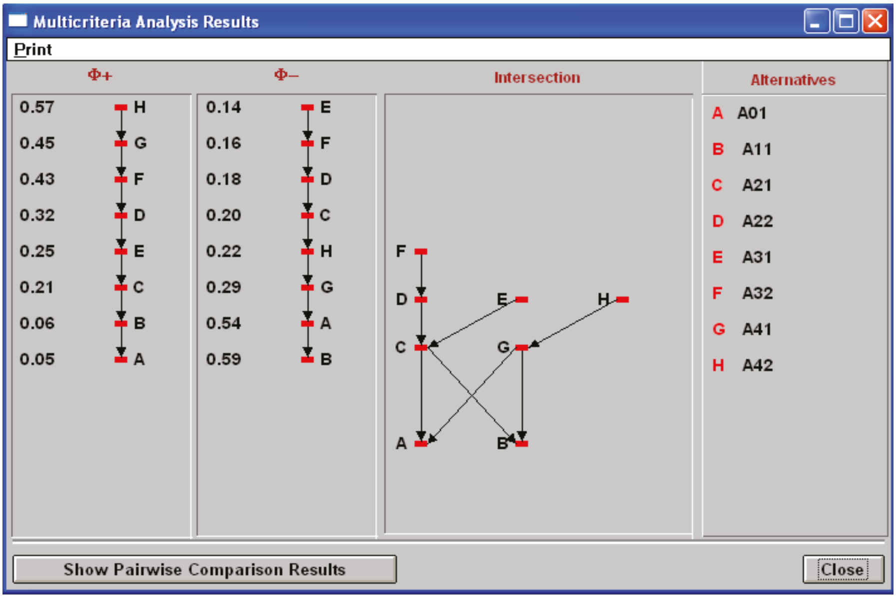

Figure A1. Indexes ф+and ф-and their intersection in the case of GSB.

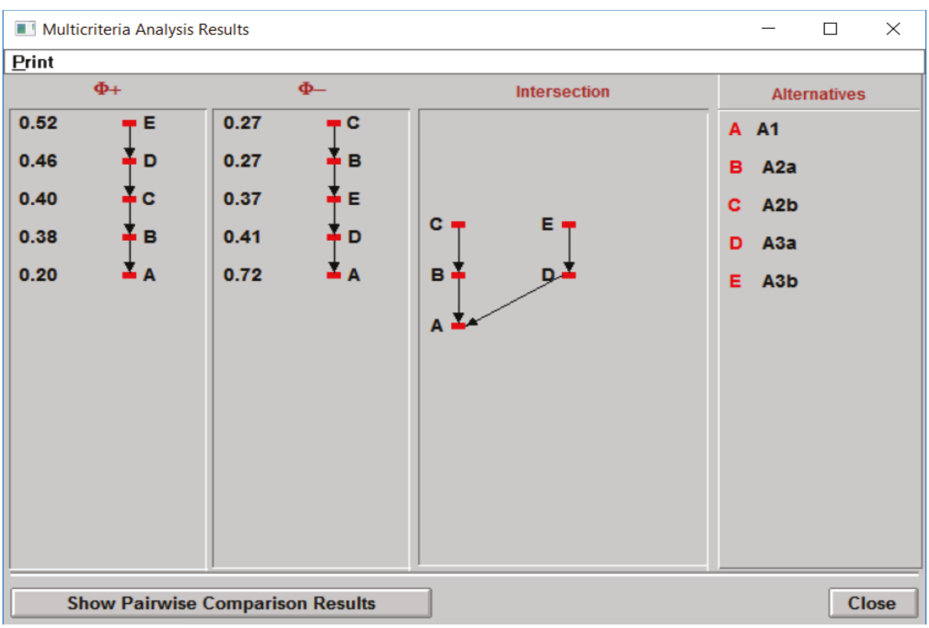

Figure A2. Indexes ф+and ф-and their intersection in the case of Mutriku.

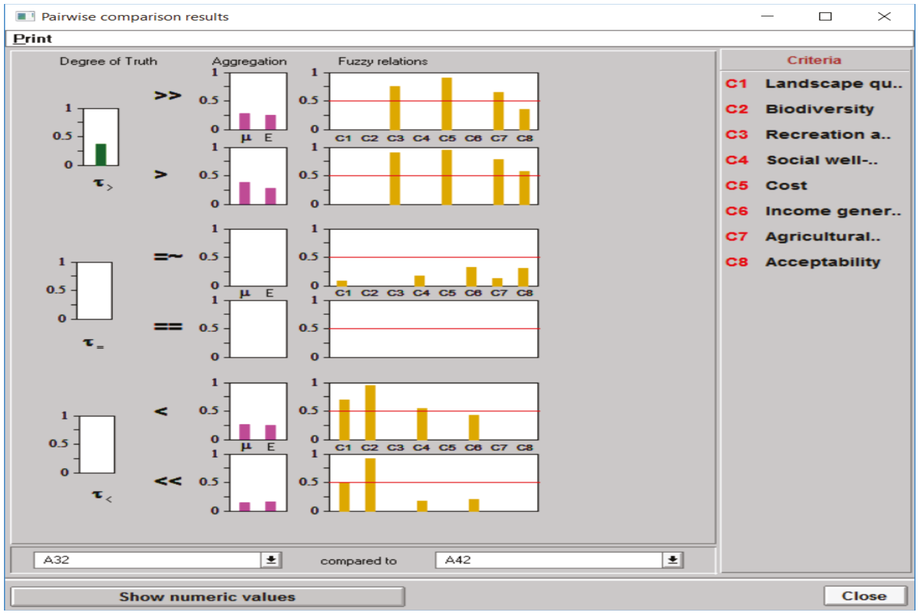

Figure A3. Comparison between A32 and A42 by evaluation criteria in the case of GSB.

Figure A4. Comparison of A2b and A3b by criteria in the case of Mutriku.

Appendix B

Table A1. Sustainability analysis: variations of γ and α in the case of GSB.

	α = 0.3			α = 0.5			α = 0.7		
	ϕ+	ϕ-	**Ranking**	ϕ+	ϕ-	**Ranking**	ϕ+	ϕ-	**Ranking**
γ = 0.1	A42	A32	1st–A32	A42	A32	1st–A32	A42	A31	1st–A32
	A32	A21	2nd–A42	A32	A31	2nd–A22	A32	A21	2nd–A42
	A22	A22	3rd–A22	A22	A22	3rd–A42	A22	A32	2nd–A31
	A41		4th–A31	A41	A21	3rd–A31	A41		2nd–A22
	A31		4th–A21	A31	A42	4th–A21	A31		3rd–A21
	A21		4th–A41	A21	A41	4th–A41	A21		3rd–A41
	A11		5th–A11	A11	A11	5th–A11	A11		4th–A11
	A01		6th–A01	A01	A01	6th–A01	A01		5th–A01
γ = 0.5	A42	A32	1st–A32	A42	A31	1st–A32	A42	A31	1st–A42
	A32	A21	2nd–A42	A32	A21	2nd–A42	A32	A21	1st–A32
	A22	A31	2nd–A22	A22	A32	2nd–A22	A22	A22	1st–A31
	A41	A22	3rd–A31	A41	A22	2nd–A31	A41	A32	1st–A22
	A31	A42	3rd–A21	A31	A42	3rd–A21	A31		2nd–A21
	A21	A11	4th–A41	A21	A41	3rd–A41	A21		2nd–A41
	A11	A41	4th–A11	A11	A11	4th–A11	A11		3rd–A11
	A01	A01	5th–A01	A01	A01	5th–A01	A01		4th–A01
γ = 0.9	A42	A21	1st–A32	A42	A31	1st–A32	A42	A31	1st–A42
	A32	A32	2nd–A42	A32	A21	2nd–A31	A41	A21	1st–A32
	A31	A31	3rd–A31	A41	A32	3rd–A42	A32	A22	1st–A31
	A41	A22	4th–A21	A22	A22	3rd–A22	A22	A32	1st–A22
	A22	A42	4th–A22	A31	A11	4th–A21	A11	A11	2nd–A41
	A21	A11	5th–A41	A11	A42	4th–A41	A31	A42	2nd–A21
	A11	A41	5th–A11	A21	A41	4th–A11	A21	A41	2nd–A11
	A01	A01	6th–A01	A01	A01	5th–A01	A01	A01	3rd–A01

Source: own elaboration.

Table A2. Sustainability analysis: variations of γ and α in the case of Mutriku.

	α = 0.3			α = 0.5			α = 0.7		
	ϕ+	ϕ-	**Ranking**	ϕ+	ϕ-	**Ranking**	ϕ+	ϕ-	**Ranking**
γ = 0.1	A3b	A2a	1st–A3b	A3b	A2b	1st–A2b	A3b	A3a	1st–A3a
	A3a	A2b	2nd–A2b	A3a	A2a	1st–A3b	A3a	A2b	2nd–A2b
	A2b	A3b	2nd–A2a	A2b	A3b	2nd–A2a	A2b	A2a	3rd–A3b
	A2a	A3a	2nd–A3a	A2a	A3a	2nd–A3a	A2a	A3b	3rd–A2a
	A1	A1	3rd–A1	A1	A1	3rd–A1	A1	A1	4th–A1
γ = 0.5	A3b	A2a	1st–A3b	A3b	A2b	1st–A2b	A3b	A2b	1st–A2b
	A3a	A2b	2nd–A2b	A3a	A2a	1st–A3b	A3a	A2a	2nd–A3b
	A2b	A3b	2nd–A2a	A2b	A3b	2nd–A2a	A2b	—	2nd–A3a
	A2a	A3a	2nd–A3a	A2a	A3a	2nd–A3a	A2a	—	2nd–A2a
	A1	A1	3rd–A1	A1	A1	3rd–A1	A1	—	3rd–A1
γ = 0.9	A3b	A2a	1st–A3b	A3b	A2b	1st–A2b	A3b	A2b	1st–A2b
	A3a	A2b	2nd–A2b	A3a	A2a	1st–A3b	A3a	A2a	1st–A3b
	A2b	A3b	2nd–A2a	A2b	—	2nd–A2a	A2b	A3b	2nd–A2a
	A2a	A3a	2nd–A3a	A2a	—	2nd–A3a	A2a	A3.a	2nd–A3a
	A1	A1	3rd–A1	A1	—	3rd–A1	A1	A1	3rd–A1

Source: own elaboration.

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A Process Oriented MCDM Approach to Construct a Circular Economy Composite Index

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Abstract: The purpose of this contribution is to develop a Circular Economy Composite indicator to benchmark EU countries performance. Europe is at the forefront of the global transition towards a sustainable and circular economy. To this end, the European Commission has launched in 2015 a Circular Economy Action Plan including a monitoring framework to measure progress and to assess the effectiveness of initiatives towards the circular economy in the European Union (EU) and Member States. Still, this monitoring framework lacks a composite indicator at the national level to aggregate the circular economy dimensions into a single summary indicator. Although there is a wide range of sustainability composite indicators, no aggregate circular economy index exits to this date. We use a multi-criteria approach to construct a circular economy composite index based on TOPSIS (Technique for Order Preferences by Similarity to Ideal Solutions) methodology. In addition, we introduce a novel aggregation methodology for building a composite indicator where different levels of compensability for the distances to the ideal and anti-ideal (or negative-ideal) values of each indicator are considered. In order to illustrate the advantages of this proposal, we have applied it to evaluate the Circular Economy performance of EU Member States for the year 2016. This proposal can be a valuable tool for identifying areas in which the countries need to concentrate their efforts to boost their circular economy performance.

Keywords: circular economy; composite indicators; multi-criteria analysis; sustainability; TOPSIS

1. Introduction

There is growing consensus on the need of a gradual transition to a more sustainable economic growth and nearly all countries are facing this challenge. The transition towards a sustainable, low carbon and resource economy requires turning linear economies based on the unidirectional material flow of production-consumption-waste models into Circular Economy (CE) models relying on production–consumption–reuse frameworks. A growing interest in CE can be also highlighted in the EU policy looking for developing guidelines to support CE strategies on the national level. Since 2015, the European Commission has launched a Circular Economy Action Plan (https://ec.europa.eu/environment/circular-economy/index_en.htm) to stimulate Europe's transition towards a more circular economy, to boost global competitiveness and to foster sustainable economic growth. The proposed actions set clear targets for reduction of waste in each step of the value chain from production, to consumption, repair and re-manufacturing, waste management, and secondary raw material that are fed back into the economy. In addition, this approach establishes a long-term path for waste management and recycling.

The highlighted importance of CE has introduced a need for monitoring its performance across countries to understand and benchmark the level of success of policy initiatives. Therefore, despite the huge variety of CE index-based methodologies, where single indices prevail, aggregate indicators in terms of composite indices are increasingly demanded by policy-makers as useful tools that could be easily interpreted and communicated to the general public.

Although the CE framework is widely explored in the literature, many contributions have pointed out the relevance of well-designed CE indicators [1–4]. The state of the art shows that a deep research on CE assessment and indicators is still lacking [5]. Several index-based methodologies have been proposed to measure the CE performance. Among them, some single indicators are focused on material flows such as the Water footprint (WF) proposed by [6] and the Material Inputs Per unit of Service (MIPS) developed by [7]. Other types of index-based methods are mainly focused on energy usage as, for example, the Cumulative Energy Demand (CED) [8] and the Embodied Energy (EE) index [9]. When addressing the issue of land use and consumption, the Ecological Footprint [10,11] or the Sustainable Process Index (SPI) [12] are remarkable. Both methodologies aim to provide a measure of the environmental pressure of human activities on the biosphere. Moreover, there are some indicators contributing in life-cycle analysis methods. On one hand, there are single indicators such as the Carbon Footprint (CF) expressed as Green House Gases emissions or the Ecosystem Damage Potential (EDP) developed by the Swiss Federal Institute of Technology. On the other hand, as examples of multiple indicators, we can cite the Life Cycle Assessment (LCA), which has been standardized by the ISO14040 international guidelines and the Environmental Performance Strategy Map (EPSM) and the sustainable Environmental Performance Indicator (SEPI).

Over the last few years, the use of Multiple Criteria Decision Making (MCMD) techniques for assessing sustainability issues has risen sharply and some authors claim that these methodologies have demonstrated their usefulness to address a wide variety of environmental and management problems [13]. In fact, sustainability assessment is a complex and multidimensional problem that requires the integration of multiple indicators to form composite indices [14], and it can be said that sustainability assessment is an MCDM problem [15]. A review of MCDM works dealing with sustainability is presented in [16]. Within the huge number of MCDM approaches, one group of them are classified as distance function based methods in which TOPSIS is included. TOPSIS is the acronym of "Technique for Order Preferences by Similarity to Ideal Solutions" [17], and it is based on aggregation functions representing the relative closeness to the ideal and anti-ideal values as reference levels. It is broadly used in MCDM frameworks due to its ease of implementation and the ability to consider a non-limited number of alternatives and criteria. According to [18] in TOPSIS, "The best alternative is the one that has the shortest distance to the ideal solution. The previous definition can also be used to demonstrate that any alternative which has the shortest distance from the ideal solution is also guaranteed to have the longest distance from the negative-ideal solution". By providing the references levels for the individual indicators, the resulting CE composite index is an easy-to-interpret measure. The distances in TOPSIS are aggregated by means of a compensatory approach, using linear functions such as the arithmetic mean than overlooks unbalances that is the disequilibrium among the sub-indicators/dimensions of the composite indicator. The arithmetic mean is the most common scheme used in the development of composite indicators [19,20]. It is also recognized as the simplest strategy and the main advantage is that it can be easily replicated by others. However, this aggregation function has attracted much criticism since the arithmetic mean performs a compensation between indicators that are not-substitutable for each other [21].

The main contribution of this paper is to introduce a process oriented approach to construct a CE composite index based on TOPSIS. When constructing a composite indicator selecting appropriate weighting and aggregation methodology is challenging [22,23]. Moreover, we consider three sustainability perspectives: weak sustainability, strong sustainability, and limited sustainability. The type of sustainability is directly related to the aggregation methodology and the level of compensability that is the possibility of offsetting the shortfall in some criteria with a superior performance in other criteria. We then face the question of aggregation different criteria into a CE composite index looking at the constant elasticity of substitution (CES) [24,25] between the dimensions previously defined in the circular economy monitoring framework. Thus, an added value of our proposal is to extend the TOPSIS method to include different levels of compensability when the distances to the ideal and negative-ideal values are aggregated. We illustrate how different choices of CES function lead to three types of circular economy composite indices (CEI): (i) Weak circular economy composite index (WCEI) allowing for unlimited substitution between circular economy indicators; (ii) Limited circular economy composite index (LCEI), allowing partial substitutability; and (iii) Strong circular economy composite index (SCEI) not allowing for any compensation.

To show the potential benefits of the proposed methodology, it has been applied to measure circular economy EU countries performance using data from the EU monitoring framework set up by the European Commission. We have considered an equal weighting scheme and three levels of compensability.

In the following sections, we first justify why measuring circular economy countries performances is important, and describe the EU monitoring framework. In the same section, we also highlight weighting and aggregation methodologies as critical issues when constructing a circular economy indicator. We then present in Section 3 the multiple criteria process oriented approach. In Section 4, an application of the proposed methodology extending the TOPSIS technique to the EU data and based on the EU Circular Economy monitoring framework is presented. Conclusions and further lines of research are provided in Section 5.

2. Measuring Circular Economy at the National Level

2.1. Why Measuring Circular Economy at the National Level Is Important

It is important to be able to measure CE at national level since CE is a key driver of sustainable development growth. In this scenario, the governments play an important role in defining and implementing policies supporting the transition from linear economies to CE based systems. Germany [26] and China [4,27] are some prime examples of CE strategies focused on the national level. In recent years, the highlighted relevance of sustainability concerns in Europe has come along with a need for monitoring CE performance across countries. It is mandatory to understand and benchmark the success of policy measures in facilitating the transition to a CE and consequently to a more sustainable growth. In 2015, the European Commission put forward a package to support the EU's transition to a circular economy contributing to boost Europe's competitiveness, modernize its economy and industry to create jobs, protect the environment, and generate sustainable growth.

Thus, making CE a reality requires a monitoring framework to show if the policy initiatives have been successful and to identify areas where more action is needed. In 2018, a Monitoring Framework for the CE was presented [28] including ten key indicators covering four broad areas such as production and consumption, waste management, secondary raw materials, and competitiveness and innovation. The data of the indicators and sub-indicators are based on official statistics coming from Eurostat, the Joint Research Centre, and the European Patent Office. The information is disseminated by the European Commission in (https://ec.europsa.eu/eurostat/web/circular-economy/indicators/monitoring-framework) through tables and a visualization tool to develop cross-country comparison.

The individual indicators are classified in four broad thematic areas: Production and Consumption, Waste Management, Secondary Raw Material and Competitiveness and Innovation. Thus, far, this monitoring framework is based on tables, graphs, and maps that evaluate a country's progress towards a circular economy by displaying all relevant indicators. After a brief summary of each area, in Table 1, the list of the key indicators is summarized together with their data source, the reference area, and the coverage period.

Table 1. List of circular economy indicators. Source: European Commission Monitoring Framework for Circular Economy (https://ec.europa.eu/eurostat/web/circular-economy/indicators/monitoring-framework).

	Indicator	Data Source	Reference Area	Coverage-Time
	Production and Consumption			
1	EU self-sufficient for raw material	European Commission	Only EU aggregate	
2	Green Public Procurement			
3	Waste generation			
3a	Generation of municipal waste per capita (Kg per capita)	European Statistical System	All EU Member States	>10 years (2000)
3b	Generation of waste excluding major mineral wastes per GDP unit (Kg per thousand euro, chain linked volumes (2010))	European Statistical System	All EU Member States	>10 years (2004)
3c	Generation of waste excluding major mineral wastes per domestic material consumption (percentage)	European Statistical System	All EU Member States	>10 years (2004)
4	Food waste (million tons)			
	Waste Management			
5	Recycling rates			
5a	Recycling rate of municipal waste (percentage)	European Statistical System	All EU Member States	>10 years (2000)
5b	Recycling rate of all waste excluding major mineral waste (percentage)	European Statistical System	All EU Member States	5 to 10 (2010)
6	Recycling/recovery for specific waste streams			
6a	Recycling rate of overall packaging (percentage)	Ministries of Environment	All EU Member States	>10 years (2000)
6b	Recycling rate of plastic packaging (percentage)	Ministries of Environment	All EU Member States	>10 years (2000)
6c	Recycling rate of wooden packaging (percentage)	Ministries of Environment	All EU Member States	>10 years (2000)
6d	Recycling rate of e-waste (percentage)	European Statistical System	All EU Member States	5 to 10 (2010)
6e	Recycling of biowaste (Kg per capita)	European Statistical System	All EU Member States	>10 years (2000)
6f	Recovery rate of construction and demolition waste (percentage)	European Statistical System	All EU Member States	5 to 10 (2010)
	Secondary Raw Materials			
7	Contribution of recycled material to raw materials demand			
7a	End-of-life recycling input rates (EOL-RIR) (percentage)	European Commission	Only EU aggregate	2016
7b	Circular material use rate (percentage)	European Statistical System	All EU Member States	>10 years (2010)
8	Trade in recyclable raw materials (tonnes)	European Statistical System	All EU Member States	>10 years (2004)
	Competitiveness and Innovation			
9	Private investments, jobs and gross value added related to CE sectors			
9a	Gross investments in tangible goods (percentage of GDP at current prices)	European Statistical System	All EU Member States	>10 years (2012)
9b	Persons employed (percentage of total employment)	European Statistical System	All EU Member States	>10 years (2012)
9c	Value added at factor cost (percentage of GDP at current prices)	European Statistical System	All EU Member States	>10 years (2012)
10	Number of patents related to recycling and secondary raw materials	European Patent Office	All EU Member States	>10 years (2000)

- **Production and consumption**. In a circular economy, more sustainable models of production in all sectors as well as a responsible consumption are needed. In the long term, this may contribute to a higher self-sufficiency of selected raw materials used in production processes. Statistical indicators related to the generation of different types of waste are used to better estimate the impact of production and consumption in the EU.
- **Waste management**. The action plan aims to increase the share of waste, which is recycled and returned into the economic cycle. The indicators and sub-indicators included in this dimension are the recycling rates to different products.
- **Secondary raw material**. In a circular economy, it is needed to use recycled materials instead of using newly extracted natural resources. Statistical indicators such as material use rates and trade of recyclable raw materials can help to assess the performance of this dimension.
- **Competitiveness and innovation**. When promoting a circular economy new jobs are created to contribute to a sustainable growth. Statistical indicators such gross investment in tangible goods, persons employed and value added are considered.

This monitoring framework displays information on EU countries performance for different CE single indicators. Currently, no composite CE indicator exists so far to show the big picture of the CE country performance.

2.2. Critical Issues When Developing a CE Composite Indicator

A composite indicator involves the combination of single indicators that represent different dimensions of a concept whose description is the objective of the analysis [22]. In recent years, there has also been a significant growth in the use of composite indicators for evaluating the performance of countries and institutions in several areas such as innovation, industrial competitiveness, or sustainable development [29–38]. Then, a composite indicator allows for measuring a set of multidimensional concepts that cannot be captured by a single indicator [39] and therefore can be a useful tool in policy making.

According to [20,39], constructing composite indicators implies the following stages:

1. Develop a theoretical framework, thus providing the basis for the selection of single indicators and the structure in sub-groups or dimensions.
2. Select the data in order to check the quality of the indicators and discuss their strengths and weaknesses.
3. Imputing the missing data, providing a measure of reliability of each imputed value.
4. Conduct a multivariate analysis in order to describe the statistical structure of the data set.
5. Apply a normalization procedure for comparability purposes.
6. Define the weighting and aggregation methodology according to the underlying theoretical framework, considering correlation and compensability issues among indicators.
7. Assess its robustness and conduct a sensitivity analysis.
8. Get back to the real data and reveal the main drivers for a good or bad performance.
9. Find links to other published indicators to correlate the composite indicator with other relevant measures.
10. Display the information through visualization tools that allows for presenting the results in a clear and accurate way.

In a benchmarking framework and especially for sustainability assessment, the right selection of the weighting and aggregation methodologies (step 6) is critical and can have important implications on countries' performances and rankings.

In the literature, weighting methods can be broadly categorized into the following groups: equal weighting, statistic based weights, and expert opinion based weights.

- Equal weighting is used when all the indicators are considered equally important and due to its simplicity appears in several sustainability indices such as the Human Development Index [40] and the Living Planet Index [41]. However, regardless of the benefits, its use has some drawbacks including validity and transparency.

- Statistic based weights derives the importance of the criteria according to the structure of the data. In this group, there are some multivariate statistical approaches such as the Principal Component Analysis (PCA) or the Factor Analysis (FA) in which the weights reflect the contribution of each indicator to the overall composite indicator. The Environmental Sustainability Index [42] uses weights derived from PCA to assess the information content of 15 sustainability sub-indices for agricultural systems. The main disadvantage of these methods is that it only works if the indicators are correlated [20]. In addition, included in this group is the benefit of the doubt approach (BOD) in which the weights are selected to maximize the index for each unit. For example, the Meta-index of Sustainable Development [43] applies the BOD for monitoring countries' overall performance in sustainable development.
- Participatory methodologies such as the Budget Allocation (BAL) [22], Analytical Hierarchy Process (AHP) [44], or Cojoint Analysis (CA) rely on expert or public opinion for indicators' weighting. For example, the Eco-Indicator 99 [45] applies the BAL for life cycle impact assessment. AHP methodology has been used to determine the weights [46] when developing a composite sustainability performance index for steel industry. In [47], the priorities of inhabitants are used as input for hierarchical conjoint analysis to improve the quality of life.

Another critical issue in developing a composite indicator that comes together with the weighting approach is the aggregation methodology. Taking into account that the aggregation technique is directly connected with the level of compensability, the choice of the aggregation rule allows for defining the range among weak or strong paradigms. Whereas a weak CE indicator allows for completing compensation among indicators, the strong CE index does not allow any compensation and thus it reflects the worst assessment achieved by a country. In the literature on composite indicators, by far the most used are additive techniques, but, due to their rigorous prerequisites, geometric or non-compensatory aggregation methods are often proposed at this stage:

- Additive aggregation (full compensability). The resulting composite indicator is the weighted arithmetic mean of normalized indicators. Although widely used, this aggregation entails restrictions on the nature of indicators such as preferential independence since it implies that the trade-off ratio between two indicators is independent of the values of the remaining indicators. By using the additive aggregation methodology, the Environmental Performance Index (EPI) ranks countries on 24 performance indicators covering environmental health and ecosystem vitality [48].
- Geometric aggregation (limited compensability). A lower compensability perspective relies on geometric-mean based methods. In this case, mutually preferential independence condition of indicators is required like in the previous case. This procedure is widely adopted for biodiversity composite indicators such as the Living Planet Index [49] or the geometric mean of relative abundance indices [50].
- Non compensatory multi-criteria approaches. As multidimensionality is intrinsic to the composite indicator concept, many works have proposed the use of MCDM techniques [51]. Some authors also claim that MCDM approaches are suitable to deal with environmental and management problems [13,14,52]. According to [39], the choice of non-compensatory multi-criteria approaches allows for finding a compromise solution among conflicting variables including non-compensability constraints. Furthermore, in recent years, there has been a sharp rise in the number of works aggregating sustainability criteria by using some MCDM tools [16]. In particular, a framework based on a multi-objective evaluation of Circular Economy development in China is presented in [53].

3. Circular Economy Index Construction

In this section, we describe the process oriented approach to construct a composite circular economy index. In the proposed procedure, we apply the multi-criteria TOPSIS methodology to get national rankings according to different levels of compensability of the aggregating functions representing "closeness to the ideal" where the chosen alternative should have the "shortest distance" from the ideal solution and the "farthest distance" from the "negative-ideal" solution. According to the stages to construct composites indicators described in Section 2.2, we propose the following steps:

Step 1. Taking into account the theoretical framework of the circular economy indicators, construct a decision matrix representing the data set $X = x_{ij}$ $(i = 1, \ldots, n; j = 1, \ldots m)$ where n denotes the number of countries and m the number of scoreboard indicators.

Step 2. Compute the normalized $R = r_{ij}$ $(n \times m)$ decision matrix for comparability purposes in which the normalized value r_{ij} is obtained by:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum x_{ij}^2}} \quad i = 1, 2, \ldots, n \quad j = 1, 2, \ldots m. \tag{1}$$

Step 3. Define the weight system $W = w_{ij}$ and calculate the weighted normalized decision matrix in which the v_{ij} value is:

$$v_{ij} = w_j \, r_{ij}, \tag{2}$$

where $w_j \in [0, 1]$ are the weights associated with each sub-criterion j and obtained according to the selected weighting system. Take into account that $\sum w_j = 1$.

Step 4. Determine the values of ideal and negative-ideal solution:

$$\begin{aligned} A_i^+ &= \{v_1^+, \ldots, v_n^+\} = \{(\max_i v_{ij} \mid j \in J_b), (\min_i v_{ij} \mid j \in J_c)\}, \\ A_i^- &= \{v_1^-, \ldots, v_n^-\} = \{(\min_i v_{ij} \mid j \in J_b), (\max_i v_{ij} \mid j \in J_c)\}, \end{aligned} \tag{3}$$

where J_b is associated with benefit criteria and J_c is associated with cost criteria.
In addition, compute the separation measures to the positive ideal $S_i{}^+$ and negative ideal $S_i{}^-$ as follows:

$$\begin{aligned} S_i^+ &= |v_{ij} - v_j^+|, \quad i = 1, 2, \ldots n, \\ S_i^- &= |v_{ij} - v_j^-|, \quad i = 1, 2, \ldots n. \end{aligned} \tag{4}$$

Step 5. Define the aggregation methodology for the separation measures. We must have in mind that the aggregation methodology can have profound implications on the overall ranking. To allow for maximum flexibility in aggregating the separation measures of the individual indicators for each dimension to the ideal and negative ideal, we use the standard constant-elasticity of substitution (CES) function [24,25] to generate the aggregated distances (D_{ij}^+, D_{ij}^-) for the country i:

$$\begin{aligned} D_{ij}^+(N_{ij}, S_{ijk}^+, \rho) &= \left[\sum_{k=1}^{Nij} \frac{1}{N_{ij}} S_{ijk}^{+\;-\rho}\right]^{-\frac{1}{\rho}}, \\ D_{ij}^-(N_{ij}, S_{ijk}^-, \rho) &= \left[\sum_{k=1}^{Nij} \frac{1}{N_{ij}} S_{ijk}^{-\;-\rho}\right]^{-\frac{1}{\rho}}, \end{aligned} \tag{5}$$

where S_{ijk}^+ and S_{ijk}^- are the separation measures to the positive and negative ideals under criteria j for country i and dimension k, respectively.

N_{ij} denotes the number of indicators for criteria in the dimension. When the aggregation is made without considering dimensions, then N_{ij} is equal to m, namely, the number of scoreboard indicators.

ρ describes the substitutability across criteria, which ranges from $-1 \leq \rho \leq \infty$.

The elasticity of substitution σ across components of the CE index is defined as:

$$\sigma = \frac{1}{1+\rho}, \tag{6}$$

with $0 \leq \sigma \leq \infty$ and

$$\rho = \frac{1-\sigma}{\sigma}. \tag{7}$$

Three special cases of CES function are proposed depending on the type of compensability allowed. A weak CE composite indicator reflects a weak sustainability perspective in which the criteria are perfect substitutes and, in this case, the CES assumes the form of the arithmetic mean (see Definition 1). On the other hand, a strong sustainability perspective occurs when the CE indicators are not substitutable, and then, when aggregating the distances in the Strong CE indicator, we opt for looking at the CES function reflecting the maximum distances to the reference levels (see Definition 2). Finally, an intermediate case of substitutability is considered reflecting the limited substitution among criteria and then the CES function becomes the geometric mean of the distances to the reference levels (see Definition 3).

Definition 1. *Weak distance. If the decision maker considers that the criteria are perfect substitutes, then $\sigma = \infty$ and $\rho = -1$. In this case, the aggregation function for the separation distances with equal weights assumes the form of the arithmetic mean:*

$$\begin{aligned} WD_{ij}^{+}(N_{ij}, S_{ijk}^{+}) &= \sum_{k=1}^{Nij} \frac{1}{N_{ij}} S_{ijk}^{+}, \\ WD_{ij}^{-}(N_{ij}, S_{ijk}^{-}) &= \sum_{k=1}^{Nij} \frac{1}{N_{ij}} S_{ijk}^{-}. \end{aligned} \tag{8}$$

Definition 2. *Strong distance. When the criteria are defined as not substitutable, then $\sigma = 0$ and $\rho = \infty$. In this case, the aggregation function for the separation distances turns into a Leontief production function and the separation measure is determined by the maximun distance to the ideal and to the negative ideal:*

$$\begin{aligned} SD_{ij}^{+}(N_{ij}, S_{ijk}^{+}) &= \max S_{ijk}^{+}, \\ SD_{ij}^{-}(N_{ij}, S_{ijk}^{-}) &= \max S_{ijk}^{-}. \end{aligned} \tag{9}$$

Definition 3. *Limited distance. For an intermediate case of substitutability, the aggregation function for the separation distances is given by the Cobb–Douglas production function with $\sigma = 1$ and $\rho = 1$. Then, the $I_{ij}^{+}(N_{ij}, I_{jk})$ and the $I_{ij}^{-}(N_{ij}, I_{jk})$ becomes the geometric mean of the criteria separation measures:*

$$\begin{aligned} LD_{ij}^{+}(N_{ij}, S_{ijk}^{+}) &= \sqcap_{k=1}^{N_{ij}} (S_{ijk}^{+})^{\frac{1}{Nij}}, \\ LD_{ij}^{-}(N_{ij}, S_{ijk}^{-}) &= \sqcap_{k=1}^{N_{ij}} (S_{ijk}^{-})^{\frac{1}{Nij}}. \end{aligned} \tag{10}$$

Step 6. Obtain the Weak Circular Economy (WCEI), the Strong Circular Economy (SCEI), and the Limited (LCEI) indices by computing the relative closeness to the ideal solution of the corresponding distances. Taking into account all the scoreboard indicators, without considering the sub-dimensions, the three types of CE indicators are computed as:

$$
\begin{aligned}
WCEI_i^* &= \frac{WD_i^-}{WD_i^- + WD_i^+} \quad i = 1, 2, \ldots, n, \\
SCEI_i^* &= \frac{SD_i^-}{SD_i^- + SD_i^+} \quad i = 1, 2, \ldots, n, \\
LCEI_i^* &= \frac{LD_i^-}{LD_i^- + LD_i^+} \quad i = 1, 2, \ldots, n.
\end{aligned}
\tag{11}
$$

In this final step, we rescale the data into a 0–100 score. This process puts all indicators on a common scale that can be compared. Finally, we rank the countries according to their relative proximity to the desirable country in descending order; thus, the higher the priority, the higher the circular economy performance.

4. Measuring Circular Economy EU Countries Performances

In this section, we apply the methodology developed in Section 3 to the data of EU Member states to obtain a Circular Economy composite index for different compensation degrees. Regarding the selection of circular economy indicators, we follow the monitoring framework set up by the European Commission to measure the progress of the EU action plan for the circular economy [28]. As stated by the EU, the selected indicators have been evaluated against how they perform in terms of relevance, acceptability, credibility, easiness, and robustness (also known as RACER). In our study, we consider only the sub-indicators with information for all the EU Member States, and we discard those for which the data are aggregated as for example the indicator 1. EU-self sufficient for raw material and 7. Contribution of recycled materials to raw material demand. In addition 2. Green Public Procurement and 4. Food waste have not been considered as they are being developed currently.

We have carried out the whole procedure defined in steps 1 to 6 starting with the values of the single indicators and calculating the WCEI, LCEI, and the SCEI composite indicators using equal weights. In Table 2, we display the values and rankings across countries of the three CE composite indices.

In Figure 1, we show the effects on the ranking of using different aggregation rules. In this figure, we should draw attention to some countries. Germany, the United Kingdom, and France lies at the top positions while Malta and Estonia come in near the bottom of the rankings. There is a small difference in the positions of France, Italy, Netherlands, Spain, Ireland, Austria, Denmark, Poland, Czequia, Slovenia, Sweden, Portugal, Hungary, Croatia, Latvia, Slovakia, Greece, Romania, Bulgaria, and Estonia. However, there is a significance deviation in countries such as: Belgium, Luxembourg, Lithuania, Luxembourg, Finland, Cyprus, and Malta. For example, Belgium and Lithuania achieve a better ranking position for weak and limited circular economy indicator while the strong circular economy composite indicator assigns an inferior position. In contrast, Finland, Cyprus, and Malta get a better position in the ranking when the circular economy performance is measured using a strong compensability rule instead of the weak or limited rule.

A more in-depth analysis of comparative performances is undertaken when the country-level data on each indicator are aggregated for each dimension. We then construct four indicators scores for production and consumption, waste management, secondary raw material, and competitiveness and innovation using the same procedure proposed in Section 3. If, for example, we consider the weak sustainability perspective proposed by Definition 1 and using Equation (8) we can obtain the corresponding dimensions scores. In Figure 2, the list of ten countries are sorted by the WCEI. This figure draws attention to the issues on which policymakers must take further action. Note that Belgium, which is currently fifth in the EU, could significantly increase its circular economy performance implementing policies aimed at improving the competitiveness and innovation area. Furthermore, this analysis reveals not only weaknesses, but also the strengths of countries, such as in the case of Netherlands, which reaches the highest score in Secondary Raw Material.

Table 2. Rank and Circular Economy composite indicator score for 28 EU countries.

Weak			Limited			Strong		
Rank	**Country**	**Score**	**Rank**	**Country**	**Score**	**Rank**	**Country**	**Score**
1	Germany	67.04	1	United Kingdom	64.4	1	Germany	68.54
2	United Kingdom	61.62	2	Germany	63.18	2	France	68.06
3	France	59.74	3	Italy	61.12	3	United Kingdom	57.51
4	Netherlands	58.25	4	Belgium	57.71	4	Spain	56.88
5	Italy	55.14	5	Netherlands	56.21	5	Netherlands	55.32
6	Belgium	51.32	6	Denmark	55.18	6	Italy	54.56
7	Spain	48.74	7	Lithuania	53.77	7	Austria	53.34
8	Austria	47.49	8	France	53.09	8	Finland	53.32
9	Denmark	46.74	9	Spain	52.27	9	Denmark	53.3
10	Lithuania	46.33	10	Poland	50.25	10	Luxembourg	53.26
11	Slovenia	44.89	11	Austria	50.05	11	Czechia	52.03
12	Poland	44.13	12	Czechia	49.96	12	Ireland	51.85
13	Czechia	43.79	13	Slovenia	48.67	13	Poland	51.63
14	Ireland	43.53	14	Ireland	46.44	14	Sweden	51.23
15	Luxembourg	43.28	15	Portugal	45.69	15	Cyprus	50.87
16	Portugal	42.95	16	Sweden	44.17	16	Belgium	50.65
17	Sweden	42.9	17	Latvia	38.33	17	Malta	50.05
18	Finland	36.7	18	Hungary	38.26	18	Slovenia	49.93
19	Latvia	36.55	19	Luxembourg	37.45	19	Portugal	49.6
20	Croatia	36.31	20	Finland	34.27	20	Greece	49.32
21	Hungary	36	21	Cyprus	34.22	21	Croatia	49.3
22	Slovakia	35.72	22	Croatia	33.47	22	Hungary	49.02
23	Bulgaria	33.66	23	Slovakia	33.27	23	Slovakia	48.48
24	Romania	31.59	24	Bulgaria	33.13	24	Latvia	48.32
25	Cyprus	30.47	25	Greece	27.13	25	Lithuania	48.09
26	Greece	29.52	26	Romania	23.63	26	Romania	47.83
27	Malta	25.38	27	Estonia	22.8	27	Bulgaria	37.13
28	Estonia	21.27	28	Malta	17.74	28	Estonia	27.94

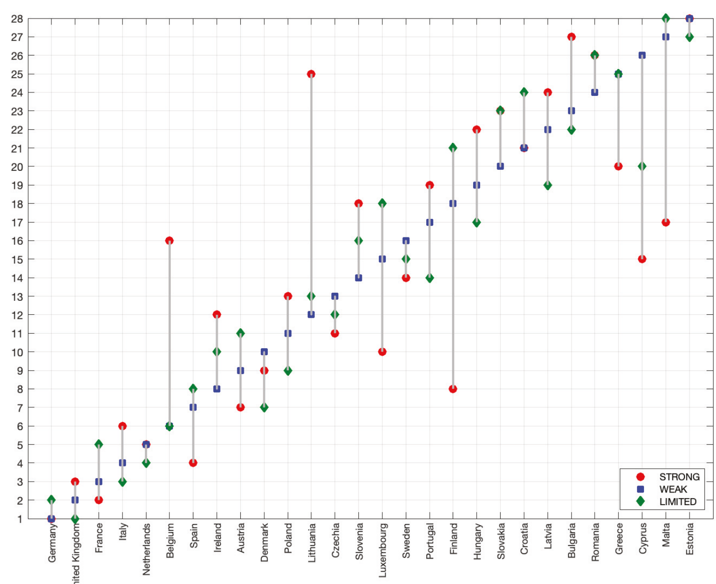

Figure 1. EU Circular Economy performance range across countries.

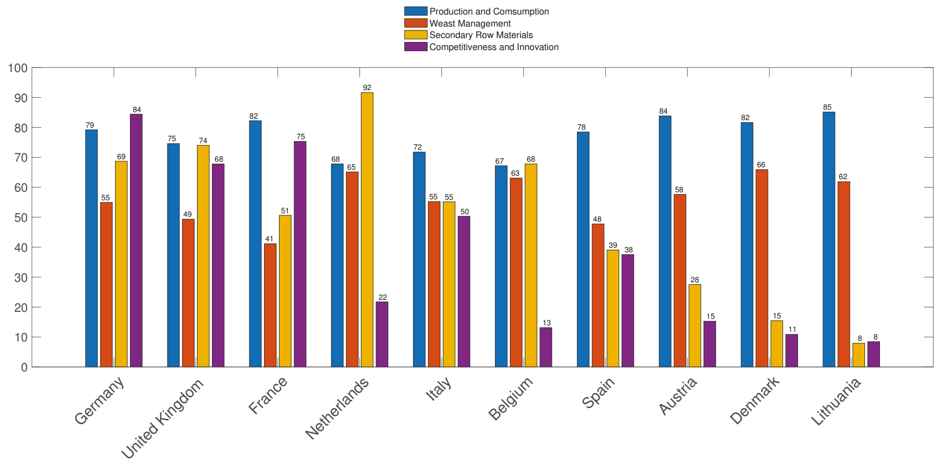

Figure 2. Top ten countries' WCEI performance for the four dimensions.

Thus, it can be concluded that, in the light of results obtained, the use of different sustainability perspectives when constructing a composite indicator affects the rankings. However, the use of three levels of compensability is highly advisable and helps to understand and interpret the results correctly. Looking at separate circular economy dimensions can be a useful tool to identify strengths and weakness at the country level.

5. Conclusions

The circular economy is now an irreversible and global mega trend [54]. A careful measurement of circular economy performance is needed to provide a foundation for effective policymaking. Recently, the European Commission has adopted a Circular Economy package trying to help businesses and consumers to make the transition to a stronger and more circular economy. However, no appropriate circular economy composite index has been developed to measure circular economy at the macro level. The main problems when constructing a composite index concern the theoretical framework, the availability of data, the selection of indicators, and how they are aggregated. Once the framework and data have been identified, we develop a process oriented approach to construct a composite circular economy index along several steps from normalization, weighting and aggregation to visualization of results. Research on composite indices provides a wide variety of aggregation methodologies, additive being the most used, although they imply a full substitutability among single indicators. In this regard, we have developed a composite indicator for different compensation degrees: weak, strong, and limited sustainability perspective.

The proposed Circular Economy Index (CEI) ranks EU countries on 17 performance indicators across ten issue categories covering production and consumption, waste management, secondary raw materials, and competitiveness and innovation. We develop a process oriented approach using the TOPSIS technique for indicator construction, which situates each country relative to the ideal and anti-ideal indicators performances. TOPSIS is a very effective method for multi-objective decision analysis due to its simplicity and its ability to consider a non limited number of alternatives and criteria in the decision-making process. The sustainability perspective varies on the choice of the level of compensability among criteria and this in turns depends on the selected aggregation technique. To this end, the aggregation is carried out by means of the constant elasticity of substitution to generate the distances to ideal and anti-ideal solutions in order to reflect three levels of compensability among individual scoreboard indicators. Moreover, the CE composite indicator has been constructed at the comprehensive level and for the four dimensions, thus providing a useful tool for policymakers to identify strengths and weaknesses of the circular economy performance at the country level.

To date, and to our knowledge, no multi-criteria circular economy composite index exists in the EU. The main advantage of our research is that, for the first time, an overall scoreboard of EU circular economy countries performance is provided. In addition, the CEI has been developed for different compensation degrees and, apart from giving an overall circular economy performance measurement, also generates early-warning signals which identity and monitor situations that warrant a higher level of concern. The CEI provides a gauge at a national scale of how close countries are to the EU circular economy strategic policy goals. The country CEI score obtained provides a scorecard in which leaders and laggards in circular economy performance are highlighted. This also leads to the identification of best practices to give additional insight and guidance for countries wishing to improve their circular economy performance.

Finally, there are several future research possibilities to overcome the limitations of our study. First, this study considers only the case of equal weighting for all the indicators and we do not check how sensitive the proposed methodology is to different weighting schemes. Thus, a Montecarlo simulation of weights could be conducted. Second, future research would be to extend the proposed model for different periods of time trying to show not only the current picture of circular economy performances at EU, but also their trends.

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Abbreviations

The following abbreviations are used in this manuscript:

EU	European Union
CE	Circular Economy
CES	Constant Elasticity of Substitution
MCDM	Multiple Criteria Decision Making
TOPSIS	Technique for Order Preferences by Similarity to Ideal Solutions
CEI	Circular Economy Index
WCEI	Weak Circular Economy Index
SCEI	Strong Circular Economy Index
LCEI	Limited Circular Economy Index

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Article

Assessment of Progress towards Achieving Sustainable Development Goals of the "Agenda 2030" by Using the CoCoSo and the Shannon Entropy Methods: The Case of the EU Countries

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Abstract: The United Nations Member States adopted the "Agenda 2030" which contains 17 sustainable development goals (SDG) that involve a certain number of targets and indicators. Although the indicators are helpful in defining the position of the current country relative to the goals' achievement, it is very complex to determine its position relative to other countries, because this requires an extensive analysis. Therefore, in this paper, the application of the multiple-criteria decision-making approach (MCDM) in defining the position of the EU (Europe Union) countries relative to the SDGs is proposed. The MCDM model is based on the Combined Compromise Solution (CoCoSo) and the Shannon Entropy methods. The final results highlight Sweden as the country that best implemented the set SD goals and has the best outputs relative to them, while Romania is in last place. The main reason for these kinds of results could be that the countries on the bottom of the list are relatively new EU members and have not been made to properly implement SDGs yet. The conclusion is that the obtained results are fully objective and rational, and that the applied model is applicable for performing this kind of analysis.

Keywords: CoCoSo method; Shannon Entropy method; "Agenda 2030"; sustainable development goals; EU countries; achievement; assessment

1. Introduction

Economic growth and industrialization have brought about many benefits, such as better standards, prosperity, and urbanization. However, this development has caused a lot of negative effects and issues on the global level that could potentially harm the well-being of future generations. Increasing industrial production in the 1960s and 1970s has led to the growth of consumerism, which was followed by massive pressure on natural resources and the environment, which eventually have led to the undermining of the nature balance [1]. Scientists and practitioners worldwide have become aware of the severity of the problem, so they started to emphasize the importance of ecological and environmental preservation, and the term sustainability was introduced. Initially, this term represented a connection between development and environment, but over time, it became broader and now includes all aspects of development, i.e., economic, social, and environmental [2]. The goals of sustainable development that are nowadays followed are somewhat different relative to those pursued in the 1990s. Acquiring new technologies, especially information and communication, has sped up the globalization process, which provoked new economic, environmental, and social challenges [3].

To define the main priorities regarding sustainable development, the United Nations in 2000 proposed the Millennium Development Goals (MDGs). The MDGs contain eight goals referred to as environment devastation, poverty, hunger, gender inequality, and school issues, which had to be achieved until 2015. During that period, some of the countries have accomplished significant improvement towards the MDGs, while others have not. Namely, the situation varied regarding the country, the goal, and the regions. However, for nearly fifteen years, the mentioned goals were at the center of attention of policy makers worldwide. This resulted in the proposing of the new set of goals called Sustainable Development Goals (SDGs), that will be in focus for the next fifteen years [4]. Namely, United Nations Members States adopted the "Agenda 2030" in 2015, which backbone is the 17 SDGs pointed to the improvement of the overall situation in the world and hence required joint action.

SDGs contain 17 goals, as is stated previously, of which goals 1–6 belong to the earlier introduced MDGs, while goals 7–17 represent the brand new goals that bring a spotlight on the new sustainability issues. Each goal includes between 5 and 12 targets and, to better monitor the progress and gained achievement relative to the set goals and targets, about 303 indicators are proposed [5]. The creation of the targets and indicators occupied a lot of the attention and caused the discussions which resulted in their assessment, with the aim to define that there is existing adequate scientific evidence for them [6,7]. The final results have shown that about 17% of the proposed targets require revision [5], and the SD Solution Network (SDSN) proposed 100 Global Monitoring indicators as reliable. Besides, some authors argue that there are inter-linkages among the goals, which, by neglecting, could cause the contradictory final results [8].

Five years have passed from the SDGs' adoption and publication of the "Agenda 2030." There is evidence of assessment of the progress towards certain SDGs. One of the topics that is elaborated, referred to in the SDGs, is under-5 child mortality in the national, regional, and global conditions [9]. Additionally, child mortality in China for the period 1996–2015 [10] and neonatal and under-5 child mortality in Africa have been investigated [11], with assessment of the significance for achieving the SD goals. Also, the scientist observed the maternity mortality from 1990 to 2015, with projections relative to achievement of the SDGs [12]. Besides, the resources needed for financing the health systems strengthening towards achieving the SDGs in the low-income and middle-income countries are estimated [13]. The questions of the achievements reached in the field of health are elaborated in the articles of the other authors as well [14–17].

Further, how different policy models contribute or hinder the achievement of the SDGs has also been investigated [18]. Pedercini et al. [19] addressed the significance of the application of the simulation integrated models as an aid for SDGs' strategy planning. Mohammed et al. [20] studied whether there is a connection between smart growths and achieving the sustainability goals, while Salvia et al. [21] assessed mentioned achievement, but from the local and global perspective. By using a few proven actual methods, Allen et al. [22] assessed the progress of Australia towards accomplishing the SDGs. Besides the given issues, the authors have discussed the assessment of land degradation [23], sustainable well-being [24], renewable energy [25], and life below water [26] regarding the achievement of the SDGs. The presented research articles show that the authors have mainly studied achievement of the particular SD goal, and not of all of them. Bearing in mind the fact that there are 17 SDGs, the problem of the assessment of the progress towards their achievement could be considered as the Multiple-Criteria Decision-Making (MCDM) problem.

The MCDM is the field of the operational research and management science that is inclusive of the various techniques pointed to facilitation of the decision-making process [27,28]. These methods are widely used in different business fields for prioritization of the given alternatives, and they contribute to the increasing of the reliability of performed decision process [29–31]. The comprehensive overview of the proposed methods could be found in the articles of the following authors: Dammak et al. [32], Zavadskas et al. [33], and Zavadskas and Turskis [34]. During the time, the authors have development of certain extensions of the proposed methods based on the fuzzy, interval, or neutrosophic numbers. The state-of-art of the introduced extensions and their applications are presented in the following articles [35,36]. As it stated previously, the MCDM methods and models find their application in resolving many real-world and business problems and, only to mention some of them: tourism [37], information technologies [38], personnel selection [39], supply chain management [40], and many more.

In the area of the assessment of the progress towards achieving the SDGs, the possibilities of the MCDM methods are not fully examined and used. Therefore, the main hypothesis of the paper is that the evaluation of the progress of the considered countries will be facilitated if the assessment approach involves the application of the MCDM methods. In that way, the position of the country towards achieving the particular goal as well as its position relative to the other countries will be determined more easily and with greater extent of reliability. As a result, the adequate methodology will be proposed and the certain conclusion concerned regarding the present situation in the field of sustainability will be derived. Because of that, in this paper is proposed the application of the hybrid model based on the Combined Compromise Solution (CoCoSo) method [41] and Shannon entropy [42,43]. The guiding idea of the paper is to propose a methodology based on the MCDM, which will facilitate the estimation process of the countries' progress towards SDGs. For demonstrating and testing the applicability of the proposed hybrid model, the 17 indicators regarding the 17 SDGs for the period 2015–2018 are introduced. The evaluation was performed based on the selected indicators connected to each goal, for which the data were available. Although the evaluation and ranking are performed for all mentioned years, because of the paper length, the computational procedure is demonstrated only for data of 2016. The structure of the paper is as below displayed: Section 1 gives an explanation of the proposed methodology; Section 2 contains the case study; in Section 3, the discussion of the results are presented, and the last section presents the conclusion.

2. Materials and Methods

2.1. Data

In order to evaluate the overall progress made by the EU countries in the implementation of the strategy, the global indicator network for SDGs is introduced by the Inter-Agency and Expert Group on SDG Indicators (IAEG-SDGs). The framework was adopted in 2017 by the General Assembly, and it is not ultimate because it will be changed if the need arises to involve new indicators or replacing the existing ones. Currently, this list includes 231 indicators, but there is a need to emphasize that the global indicator framework actually involves 247 indicators, because twelve indicators repeat under certain targets [44]. For this paper, the 17 indicators relative to the 17 goals were chosen and involved in the evaluation model. The goals, relative indicators, and explanations of the indicators are presented in Table 1.

Table 1. Goals and selected indicators.

Goal		Indicator		Explanation
Goal 1	No poverty	I_1	People at risk of income poverty after social transfers	The persons at risk of poverty and with an equalized disposable income below the risk-of-poverty limit, which is set at 60% of the national median equalized disposable income (after social transfers).
Goal 2	Zero hunger	I_2	Government support to agricultural research and development	The indicator is related to the Government Budget Appropriations or Outlays on research and development (GBAORD) which estimate government support to R&D activities.
Goal 3	Good health and well-being	I_3	Self-reported unmet need for medical examination and care by sex	The indicator estimates the share of the population aged 16 and over who report an unmet need for medical care because of certain reasons.
Goal 4	Quality education	I_4	Tertiary educational attainment by sex	The indicator is pointed to the share of the population between the ages of 30–34 who have successfully finished tertiary studies.
Goal 5	Gender equality	I_5	Positions held by women in senior management positions	The indicator estimates the share of females who are board members in the companies which shares are traded on the stock exchange.
Goal 6	Clean water and sanitation	I_6	Population having neither a bath, nor a shower, nor indoor flushing toilet in their household by poverty status	The indicator represents the share of the population that does not have a bathroom and indoor toilet.
Goal 7	Affordable and clean energy	I_7	Greenhouse gas (GHG) emissions intensity of energy consumption	The indicators shows emitted number of tonnes of CO_2 equivalents of energy-related GHGs in particular economy per unit of consumed energy.

Table 1. *Cont.*

Goal			Indicator	Explanation
Goal 8	Decent work and economic growth	I_8	Real GDP per capita	The indicator represents the ratio computed by putting in the relation the real gross domestic product (GDP) to the average population of the specific year.
Goal 9	Industry, innovation and infrastructure	I_9	Gross domestic expenditure on R&D by sector	The indicator estimates gross domestic expenditure on R&D (GERD) as a percentage of the gross domestic product (GDP).
Goal 10	Reduced inequalities	I_{10}	Purchasing power adjusted GDP per capita	Gross domestic product (GDP) is a measure for the economic activity, while GDP per capita is calculated as the ratio of GDP to the average population in a particular year.
Goal 11	Sustainable cities and communities	I_{11}	Recycling rate of municipal waste	The indicator estimates the tonnage recycled from municipal waste divided by the total municipal waste arising.
Goal 12	Responsible consumption and production	I_{12}	Generation of waste excluding major mineral wastes by hazardousness	The indicator estimates all waste produced in a country.
Goal 13	Climate action	I_{13}	Greenhouse gas emissions	The indicator estimates the total national emissions.
Goal 14	Life below water	I_{14}	Bathing sites with excellent water quality by locality	The indicator estimates the number and proportion of coastal and inland bathing sites with high quality of water.
Goal 15	Life on land	I_{15}	Surface of terrestrial sites designated under Natura 2000	The indicator estimates the surface of terrestrial sites designated under Natura 2000.
Goal 16	Peace, justice, and strong institutions	I_{16}	Population reporting occurrence of crime, violence, or vandalism in their area by poverty status	The indicator shows the share of people who reported that they have a problem with crime, violence, and vandalism in their district.
Goal 17	Partnerships for the goals	I_{17}	Official development assistance as share of gross national income	The promoting of economic development in recipient countries by using official development assistance (ODA) that involves grants or loans initiated by the official sector.

Source: Eurostat [45].

The main reason for the selection of the presented indicators relies on the fact that they realistically picture the core of the considered goals by themselves. By involving all of the proposed indicators, two problems will arise: firstly, the model will be too extensive and complex to manage, and secondly, some of the indicators repeat in several goals which, eventually, could lead to inadequate results.

2.2. Methods

2.2.1. Combined Compromise Solution Method

The Combined Compromise Solution (CoCoSo) method was proposed by Yazdani et al. [41]. The CoCoSo method is based on the integration of weighted sum method and exponentially weighted product method, as follows:

$$S_i = \sum\nolimits_{j=1}^{n} r_{\text{ij}} w_j, \tag{1}$$

$$P_i = \sum\nolimits_{j=1}^{n} r_{\text{ij}}^{w_j}, \tag{2}$$

where *Si* and *Pi* denote the sum of weighted comparability sequence and power-weighted comparability sequences of alternative i, respectively, w_j denotes weight of criterion j, and r_{ij} denotes normalized rating of alternative i according to criterion j, that is calculated as follows:

$$r_{\text{ij}} = \begin{cases} \frac{x_{\text{ij}} - \min\limits_i x_{\text{ij}}}{\max\limits_i x_{\text{ij}} - \min\limits_i x_{\text{ij}}}; & \text{when criterion } j \text{ is benefit} \\ \frac{\max\limits_i x_{\text{ij}} - x_{\text{ij}}}{\max\limits_i x_{\text{ij}} - \min\limits_i x_{\text{ij}}}; & \text{when criterion } j \text{ is } \cos \text{t} \end{cases}, \tag{3}$$

where x_{ij} denotes rating of alternative i according to criterion j.

For ranking alternatives, the CoCoSo method uses relative performance score k_i, that is calculated based on three aggregated appraisal scores k_{ia}, k_{ib}, and k_{ic}, as follows:

$$k_i = \frac{1}{3}(k_{\text{ia}} + k_{\text{ib}} + k_{\text{ic}}) + (k_{\text{ia}} k_{\text{ib}} k_{\text{ic}})^{\frac{1}{3}}, \tag{4}$$

with:

$$k_{\text{ia}} = \frac{S_i + P_i}{\sum_{i=1}^{m}(S_i + P_i)}, \tag{5}$$

$$k_{\text{ib}} = \frac{S_i}{\min\limits_i S_i} + \frac{P_i}{\min\limits_i P_i}, \tag{6}$$

$$k_{ic} = \frac{\lambda S_i + (1-\lambda)P_i}{\lambda \max_i Si + (1-\lambda)\max_i P_i}, \quad (7)$$

where λ is coefficient, $\lambda \in [0,1]$, and it is often set to $\lambda = 0.5$.

2.2.2. Entropy Method

Entropy Method is a well-known approach that is often used for determining objective criteria weights [46]. Based on Wang and Lee [47], the procedure for determining criteria weights using entropy method is as follows:

$$w_j = \frac{1-e_j}{\sum_{j=1}^{n}\left(1-e_j\right)}, \quad (8)$$

with:

$$e_j = -\frac{1}{\ln(m)} \sum_{i=1}^{m} r_{ij} \ln\left(r_{ij}\right), \quad (9)$$

where r_{ij} denotes normalized rating of alternative i in relation to criterion j, m is number of evaluating objects, n is number of criteria.

The normalized ratings are calculated as follows:

$$r_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}}. \quad (10)$$

3. Results

The assessing progress towards achieving the goals defined by the implementation of the "Agenda 2030" strategy by using CoCoSo and the Entropy methods, shown in Figure 1, can be also expressed by applying the following steps:

Step 1. Selection of indicators for evaluation
Step 2. Data collection
Step 3. Determining the significance of indicators
Step 4. Selection of countries for evaluation
Step 5. Evaluation of selected countries
Step 6. Ranking and comparison of selected countries

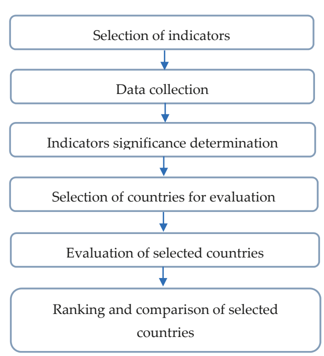

Figure 1. The assessing progress by using CoCoSo and the Entropy methods.

In this case, 27 EU countries have been evaluated based on 17 indicators adopted from "Agenda 2030" for the period 2015–2018. Due to the paper length, the computational procedure is presented only for 2016. The indicators used for evaluation are shown in Table 1 and the data regarding the considered indicators for the EU countries are presented in Table 2.

Table 2. Initial decision-making matrix according to "Agenda 2030" for 2016.

	I_1	I_2	I_3	I_4	I_5	I_6	I_7	I_8	I_9	I_{10}	I_{11}	I_{12}	I_{13}	I_{14}	I_{15}	I_{16}	I_{17}
Belgium	15.5	37.10	99.3	45.6	28.6	0.1	36.4	34,690	2.52	33,900	53.5	3383	80.3	1271	3887	13.3	0.50
Bulgaria	22.9	15.71	193.9	33.8	15.3	10.7	9.7	6050	0.77	13,900	31.8	2527	58.2	2827	38,222	25.0	0.13
Czechia	9.7	41.07	135.0	32.8	10.1	0.2	24.8	16,520	1.68	24,900	33.6	1214	65.8	0	11,148	11.7	0.14
Denmark	11.9	96.57	108.9	46.5	27.1	0.5	14.6	46,720	3.09	36,100	46.7	1657	73.5	19,053	3594	8.4	0.75
Germany	16.5	824.67	112.0	33.2	29.5	0.0	216.9	34,700	2.94	35,100	67.1	1897	74.2	25,603	55,200	14.1	0.70
Estonia	21.7	6.49	155.8	45.4	8.8	5.1	2.8	13,650	1.25	21,700	28.1	8965	48.9	6754	8083	9.2	0.19
Ireland	16.8	95.40	96.8	54.6	16.5	0.2	11.6	50,710	1.17	50,000	40.7	1765	113.1	10,259	9226	9.7	0.32
Greece	21.2	32.98	119.4	42.7	9.1	0.2	16.8	17,110	0.99	19,300	17.2	1328	89.8	7199	35,747	11.8	0.19
Spain	22.3	401.44	94.7	40.1	20.3	0.3	82.2	23,760	1.19	25,900	33.9	1480	116.7	84,404	137,872	10.3	0.34
France	13.6	351.05	101.8	43.7	41.2	0.3	149.3	31,770	2.22	29,800	41.9	1455	85.8	41,685	70,515	14.8	0.38
Croatia	19.5	8.42	169.8	29.3	19.9	1.4	6.6	11,100	0.86	17,200	21.0	828	76.5	4986	20,704	3.0	0.07
Italy	20.6	274.80	84.6	26.2	32.3	0.1	115.9	26,020	1.37	27,700	45.9	1799	84.8	6806	57,173	14.7	0.27
Cyprus	16.1	5.51	82.4	53.4	10.8	0.7	1.8	22,360	0.52	24,700	17.2	839	150.6	131	1653	9.8	0.00
Latvia	21.8	11.00	216.6	42.8	28.5	11.7	3.8	11,030	0.44	18,300	25.2	1065	44.0	4387	7446	10.0	0.11
Lithuania	21.9	7.71	224.4	58.7	14.3	12.0	5.1	12,040	0.84	21,500	48.0	1223	42.1	1563	8086	3.4	0.14
Luxembourg	16.5	0.14	94.7	54.6	12.9	0.5	4.0	82,880	1.30	76,600	48.2	2697	87.9	0	702	12.2	1.00
Hungary	14.5	31.97	243.7	33.0	12.3	3.8	17.8	11,410	1.19	19,200	34.7	1119	65.6	0	19,949	9.7	0.17
Malta	16.5	0.28	101.6	32.0	4.5	0.0	0.6	20,260	0.57	27,000	7.0	1276	98.8	3490	41	10.4	0.20
Netherlands	12.7	104.84	97.3	45.7	27.5	0.1	49.8	39,810	2.00	36,300	53.5	2539	91.7	15,083	5520	16.9	0.65
Austria	14.1	32.13	103.7	40.1	18.1	0.2	28.1	36,430	3.12	36,500	57.6	1886	103.0	0	12,691	12.4	0.42
Poland	17.3	53.15	153.7	44.6	18.8	2.3	66.6	11,260	0.96	19,400	34.8	2090	84.5	7236	61,165	5.6	0.15
Portugal	19.0	18.56	115.5	34.6	14.3	0.9	16.2	17,010	1.28	21,900	30.9	1148	114.4	31,885	19,010	7.8	0.17
Romania	25.3	24.06	229.8	25.6	10.1	30.0	22.2	7720	0.48	16,900	13.3	1084	46.3	6362	54,214	14.1	0.11
Slovenia	13.9	6.92	114.7	44.2	24.8	0.2	4.9	18,540	2.01	23,500	55.6	1457	94.9	11	7675	8.5	0.19
Slovakia	12.7	9.58	183.1	31.5	12.5	0.8	10.4	14,550	0.79	20,600	23.0	1459	57.6	0	14,442	6.9	0.12
Finland	11.6	76.28	101.0	46.1	30.1	0.3	25.2	35,300	2.72	31,200	42.0	2595	83.1	7140	42,495	6.5	0.44
Sweden	16.2	51.85	78.7	51.0	36.9	0.0	32.1	42,910	3.25	35,000	48.4	2136	76.4	20,229	55,280	12.7	0.94

Source: Eurostat [45].

Normalized decision-making matrix, constructed using Equation (2), is shown in Table 3. The significances of indicators, obtained using Equations (8)–(11), and optimization directions of indicators are also shown in Table 3.

Table 3. Normalized decision-making matrix.

	I_1	I_2	I_3	I_4	I_5	I_6	I_7	I_8	I_9	I_{10}	I_{11}	I_{12}	I_{13}	I_{14}	I_{15}	I_{16}	I_{17}
Weights	0.07	0.06	0.07	0.05	0.05	0.07	0.07	0.05	0.05	0.05	0.05	0.07	0.07	0.06	0.05	0.07	0.05
Optimization	min	max	min	max	max	min	min	max	max	max	max	min	min	max	max	min	max
Belgium	0.63	0.04	0.88	0.60	0.66	1.00	0.83	0.37	0.74	0.32	0.77	0.69	0.65	0.02	0.03	0.53	0.50
Bulgaria	0.15	0.02	0.30	0.25	0.29	0.64	0.96	0.00	0.12	0.00	0.41	0.79	0.85	0.03	0.28	0.00	0.13
Czechia	1.00	0.05	0.66	0.22	0.15	0.99	0.89	0.14	0.44	0.18	0.44	0.95	0.78	0.00	0.08	0.60	0.14
Denmark	0.86	0.12	0.82	0.63	0.62	0.98	0.94	0.53	0.94	0.35	0.66	0.90	0.71	0.23	0.03	0.75	0.75
Germany	0.56	1.00	0.80	0.23	0.68	1.00	0.00	0.37	0.89	0.34	1.00	0.87	0.70	0.30	0.40	0.50	0.70
Estonia	0.23	0.01	0.53	0.60	0.12	0.83	0.99	0.10	0.29	0.12	0.35	0.00	0.94	0.08	0.06	0.72	0.19
Ireland	0.54	0.12	0.89	0.88	0.33	0.99	0.95	0.58	0.26	0.58	0.56	0.88	0.35	0.12	0.07	0.70	0.32
Greece	0.26	0.04	0.75	0.52	0.13	0.99	0.93	0.14	0.20	0.09	0.17	0.94	0.56	0.09	0.26	0.60	0.19
Spain	0.19	0.49	0.90	0.44	0.43	0.99	0.62	0.23	0.27	0.19	0.45	0.92	0.31	1.00	1.00	0.67	0.34
France	0.75	0.43	0.86	0.55	1.00	0.99	0.31	0.33	0.63	0.25	0.58	0.92	0.60	0.49	0.51	0.46	0.38
Croatia	0.37	0.01	0.45	0.11	0.42	0.95	0.97	0.07	0.15	0.05	0.23	1.00	0.68	0.06	0.15	1.00	0.07
Italy	0.30	0.33	0.96	0.02	0.76	1.00	0.47	0.26	0.33	0.22	0.65	0.88	0.61	0.08	0.41	0.47	0.27
Cyprus	0.59	0.01	0.98	0.84	0.17	0.98	0.99	0.21	0.03	0.17	0.17	1.00	0.00	0.00	0.01	0.69	0.00
Latvia	0.22	0.01	0.16	0.52	0.65	0.61	0.99	0.06	0.00	0.07	0.30	0.97	0.98	0.05	0.05	0.68	0.11
Lithuania	0.22	0.01	0.12	1.00	0.27	0.60	0.98	0.08	0.14	0.12	0.68	0.95	1.00	0.02	0.06	0.98	0.14
Luxembourg	0.56	0.00	0.90	0.88	0.23	0.98	0.98	1.00	0.31	1.00	0.69	0.77	0.58	0.00	0.00	0.58	1.00
Hungary	0.69	0.04	0.00	0.22	0.21	0.87	0.92	0.07	0.27	0.08	0.46	0.96	0.78	0.00	0.14	0.70	0.17
Malta	0.56	0.00	0.86	0.19	0.00	1.00	1.00	0.18	0.05	0.21	0.00	0.94	0.48	0.04	0.00	0.66	0.20
Netherlands	0.81	0.13	0.89	0.61	0.63	1.00	0.77	0.44	0.56	0.36	0.77	0.79	0.54	0.18	0.04	0.37	0.65
Austria	0.72	0.04	0.85	0.44	0.37	0.99	0.87	0.40	0.95	0.36	0.84	0.87	0.44	0.00	0.09	0.57	0.42
Poland	0.51	0.06	0.55	0.57	0.39	0.92	0.69	0.07	0.19	0.09	0.46	0.84	0.61	0.09	0.44	0.88	0.15
Portugal	0.40	0.02	0.78	0.27	0.27	0.97	0.93	0.14	0.30	0.13	0.40	0.96	0.33	0.38	0.14	0.78	0.17
Romania	0.00	0.03	0.08	0.00	0.15	0.00	0.90	0.02	0.01	0.05	0.10	0.97	0.96	0.08	0.39	0.50	0.11
Slovenia	0.73	0.01	0.78	0.56	0.55	0.99	0.98	0.16	0.56	0.15	0.81	0.92	0.51	0.00	0.06	0.75	0.19
Slovakia	0.81	0.01	0.37	0.18	0.22	0.97	0.95	0.11	0.12	0.11	0.27	0.92	0.86	0.00	0.10	0.82	0.12
Finland	0.88	0.09	0.86	0.62	0.70	0.99	0.89	0.38	0.81	0.28	0.58	0.78	0.62	0.08	0.31	0.84	0.44
Sweden	0.58	0.06	1.00	0.77	0.88	1.00	0.85	0.48	1.00	0.34	0.69	0.84	0.68	0.24	0.40	0.56	0.94

Source: Author's calculation.

Based on data from Table 4, the sum of weighted and power-weighted comparability sequences are calculated, using Equations (1) and (2), as it is shown in Table 4. Values of three aggregated appraisal scores k_{ia}, k_{ib}, and k_{ic}, obtained using Equations (5)–(7), are also presented in Table 4.

Table 4. Calculation details obtained using the CoCoSo method.

	S_i	P_i	k_{ia}	k_{ib}	k_{ic}
Belgium	0.56	16.08	0.039	3.28	0.97
Bulgaria	0.33	12.92	0.031	2.20	0.77
Czechia	0.49	15.09	0.037	2.95	0.91
Denmark	0.65	16.37	0.040	3.64	0.99
Germany	0.61	15.53	0.038	3.42	0.94
Estonia	0.38	14.76	0.036	2.55	0.88
Ireland	0.55	16.21	0.039	3.27	0.98
Greece	0.43	15.84	0.038	2.81	0.95
Spain	0.57	16.31	0.040	3.33	0.98
France	0.60	16.43	0.040	3.46	0.99
Croatia	0.43	15.66	0.038	2.80	0.94
Italy	0.49	16.05	0.039	3.03	0.96
Cyprus	0.43	13.65	0.033	2.64	0.82
Latvia	0.41	14.72	0.036	2.62	0.88
Lithuania	0.45	15.64	0.038	2.87	0.94
Luxembourg	0.62	14.45	0.035	3.38	0.88
Hungary	0.42	14.06	0.034	2.61	0.84
Malta	0.42	12.85	0.031	2.51	0.77
Netherlands	0.57	16.27	0.040	3.35	0.98
Austria	0.56	15.32	0.037	3.22	0.93
Poland	0.47	15.97	0.039	2.94	0.96
Portugal	0.46	15.95	0.039	2.92	0.96
Romania	0.28	12.59	0.030	2.00	0.75
Slovenia	0.54	15.74	0.038	3.18	0.95
Slovakia	0.45	14.90	0.036	2.79	0.89
Finland	0.62	16.36	0.040	3.51	0.99
Sweden	0.67	16.47	0.040	3.72	1.00

Source: Author's calculation.

The assessments of progress based on the three scores k_{ia}, k_{ib}, and k_{ic} are shown in Figure 2, while the impact of coefficient λ to the k_{ic} is shown in Figure 3.

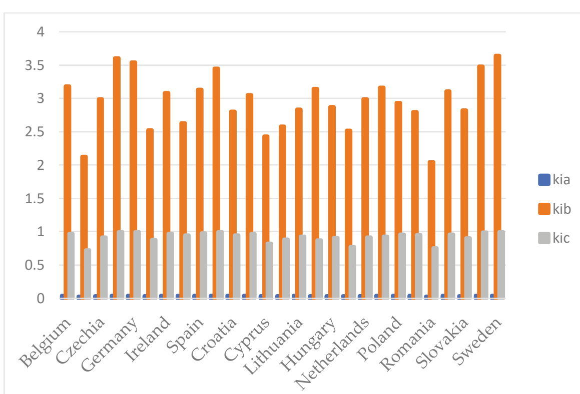

Figure 2. Assessments of progress based on the three scores k_{ia}, k_{ib}, and k_{ic}.

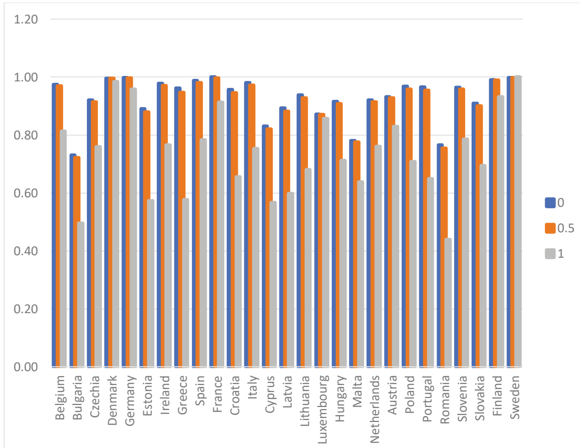

Figure 3. Impact of coefficient λ on k_{ic}.

Assessment of progress towards achieving sustainable development goals of the "Agenda 2030" for 2016 has been done based on relative performance score k_i, calculated using Equation (4), as it is shown in Table 5 and in Figure 4.

Table 5. Assessment of progress towards achieving sustainable development goals of the "Agenda 2030" for 2016.

	k_i	Rank
Belgium	1.89	6
Bulgaria	1.31	26
Czechia	1.78	15
Denmark	2.07	2
Germany	2.05	3
Estonia	1.57	23
Ireland	1.85	10
Greece	1.66	21
Spain	1.88	7
France	2.01	5
Croatia	1.73	19
Italy	1.84	11
Cyprus	1.50	25
Latvia	1.60	22
Lithuania	1.73	18
Luxembourg	1.81	12
Hungary	1.73	17
Malta	1.50	24
Netherlands	1.78	14
Austria	1.86	8
Poland	1.79	13
Portugal	1.73	16
Romania	1.31	27
Slovenia	1.85	9
Slovakia	1.71	20
Finland	2.02	4
Sweden	2.09	1

Source: Author's calculation.

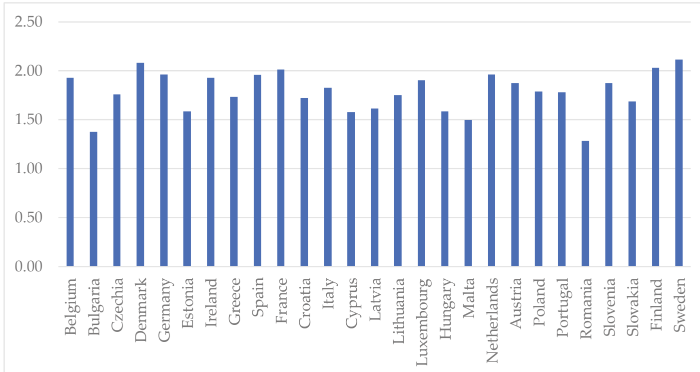

Figure 4. Assessment of progress towards achieving sustainable development goals of the "Agenda 2030" for 2016.

To verify obtained results about assessment of progress, similar calculations have been done with the WASAS method and SAW method with two different normalization procedures that are used in the CoCoSo and WASPAS methods. Obtained results are shown in Table 6 and Figure 5.

Table 6. Comparison of results obtained using the CoCoSo, WASPAS and SAW methods.

	CoCoSo	WASPAS	SAW (mx-min)	SAW(max)
Belgium	9	11	10	11
Bulgaria	26	27	26	27
Czechia	16	22	14	17
Denmark	2	4	2	4
Germany	5	2	5	1
Estonia	22	23	25	25
Ireland	8	8	11	12
Greece	18	19	21	24
Spain	7	5	8	5
France	4	3	6	3
Croatia	19	15	20	16
Italy	13	10	13	13
Cyprus	24	21	19	18
Latvia	21	20	24	21
Lithuania	17	13	17	14
Luxembourg	10	12	3	6
Hungary	23	25	22	22
Malta	25	9	23	9
Netherlands	6	7	7	8
Austria	12	17	9	10
Poland	14	18	15	20
Portugal	15	16	16	19
Romania	27	24	27	26
Slovenia	11	14	12	15
Slovakia	20	26	18	23
Finland	3	6	4	7
Sweden	1	1	1	2

Source: Author's calculation.

As it can be seen from Table 6, results obtained using the CoCoSo method are similar, or very similar, with results obtained using the WASPAS and SAW methods.

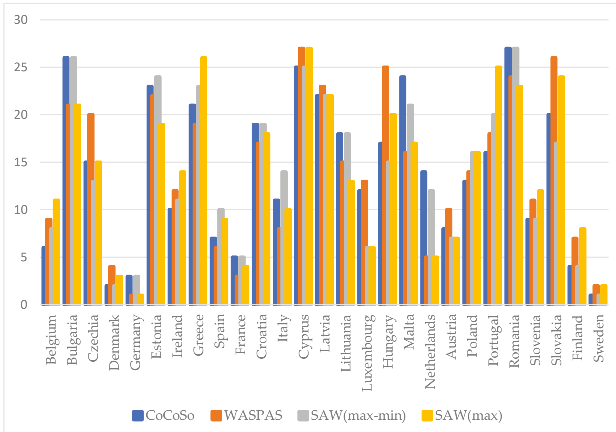

Figure 5. Comparison of results obtained using the CoCoSo, WASPAS and SAW methods.

The comparison of the introduced methodology with the proved methods such as WASPAS and SAW confirmed its applicability and the reliability of the obtained results. Therefore, we applied the proposed methodology on the data for 2015, 2017, and 2018 year to provide a more complete picture about the current state regarding the achievement of the SDGs. The gained results are presented in Table 7 and Figure 6.

Table 7. Assessment of progress towards achieving sustainable development goals of the "Agenda 2030" for the period 2015–2018.

	2015	Rank	2016	Rank	2017	Rank	2018	Rank
Belgium	1.91	9	1.89	6	1.87	7	1.87	7
Bulgaria	1.28	27	1.31	26	1.28	26	1.29	27
Czechia	1.85	11	1.78	15	1.79	13	1.80	12
Denmark	2.15	2	2.07	2	2.06	2	2.06	2
Germany	2.09	5	2.05	3	2.04	3	2.06	3
Estonia	1.64	23	1.57	23	1.48	24	1.53	24
Ireland	1.79	16	1.85	10	1.85	9	1.74	17
Greece	1.68	21	1.66	21	1.64	22	1.54	23
Spain	1.91	8	1.88	7	1.86	8	1.87	8
France	2.10	4	2.01	5	2.01	4	2.01	4
Croatia	1.74	20	1.73	19	1.71	18	1.74	19
Italy	1.79	15	1.84	11	1.87	6	1.88	6
Cyprus	1.48	25	1.50	25	1.47	25	1.44	25
Latvia	1.66	22	1.60	22	1.65	21	1.61	22
Lithuania	1.78	17	1.73	18	1.70	19	1.66	20
Luxembourg	1.82	13	1.81	12	1.77	15	1.78	13
Hungary	1.80	14	1.73	17	1.73	16	1.75	15
Malta	1.61	24	1.50	24	1.55	23	1.64	21
Netherlands	1.85	10	1.78	14	1.78	14	1.77	14
Austria	1.92	7	1.86	8	1.82	10	1.85	9
Poland	1.83	12	1.79	13	1.80	12	1.82	11
Portugal	1.75	19	1.73	16	1.70	20	1.74	18
Romania	1.33	26	1.31	27	1.26	27	1.30	26
Slovenia	1.92	6	1.85	9	1.82	11	1.83	10
Slovakia	1.77	18	1.71	20	1.71	17	1.75	16
Finland	2.10	3	2.02	4	2.00	5	1.98	5
Sweden	2.17	1	2.09	1	2.07	1	2.08	1

Source: Author's calculation.

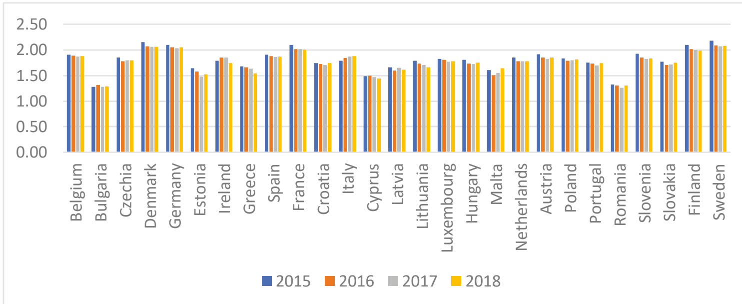

Figure 6. Assessment of progress towards achieving sustainable development goals of the "Agenda 2030" for the period 2015–2018.

4. Discussion

According to the obtained results, the countries that have made the greatest prosperity towards the SDGs for the period 2015–2018 are as follows: Sweden, Denmark, Germany, France, and Finland. The final results emphasize Sweden as a country that makes the most significant progress towards achievement of the set goals of the "Agenda 2030." Observation of the input data shows that the gained achievement is not the best in all segments. Despite that, Sweden makes stable and equable progress towards all considered goals. In some areas, such as gross domestic expenditure on R&D by sector, Sweden has the best results from all EU countries. Achievements of Sweden relative to the "Agenda 2030" and expressed results have never been among the worst, but always between medium and the best, which placed Sweden as a country which makes the most considerable progress towards set SDGs.

It is interesting to note that the best-ranked countries belong to Scandinavia and Northern Europe (Sweden, Denmark, and Finland), and Western Europe (France and Germany). Besides, all of these countries joined the EU quietly long since. To be more precise, France and Germany joined the EU in 1957, Denmark in 1973, while Sweden and Finland joined the EU in 1995. The reason for good results in incorporating the positive practice relative to achievement of the sustainable development goals is that the people who live in this part of the Europe much longer work on the adopting of this practice because they are longer in the aegis of the EU. The fact that led to this kind of conclusion is as follows: on the last two positions are Bulgaria (1.38) and Romania (1.28). Both of the mentioned countries are located in Eastern Europe and both joined the EU in 2007. What does this mean? This means that these countries have not incorporated sustainability as a postulate in their policies properly, yet. They should invest time and energy in order to change the point of view and attitude towards the question of sustainable development and sustainable goals. The key issues with which Bulgaria and Romania are faced with are: poverty, high death rate, a lot of households without a bathroom and toilet in the house, low real GDP per capita, low gross domestic expenditure on R&D, low purchasing power, insufficient recycling, high rate of crime and violation. Only resolving of all the mentioned problems and improvement of all considered aspects could change the current state in the given countries and enable them to compete with first positioned countries. Only in that way, they will improve the present position and make achievement relative to the set SDGs and requirements of the "Agenda 2030."

Furthermore, the countries that possessed the first five places have relatively high GDP per capita. For illustration, according to the data from the Eurostat [48], average GDP per capita of the first-ranked Sweden for the period 2015–2018 amounts to 46,865 euros. That amount for the same period for Denmark, Finland, Germany, and France is 50,045 euros, 40,382.5 euros, 38,687.5 euros, and 33,950 euros, respectively. Romania, which is in the last position, has the GDP per capita which is five times smaller than, for example, the GDP of Sweden. The higher GDP per capita does not guarantee better achievements towards the set goals. The example of that is Luxembourg, which has extremely high GDP per capita but it is on the twelfth to fifteenth position considering the progress towards SDGs for the observed period of time. The higher GDP points to the economic stability and prosperity of the certain country, but these do not mean that the country is automatically committed to the sustainability goals. Thus, it is evident that the countries with medium-to-high GDP per capita gain better results than that one with quite small GDP per capita. Additionally, the average net income of the households of the best-ranked countries is very high for the analyzed period of time and, for example, for the Sweden amounted to 25,559 euros in 2018 [49]. On the contrary, the net income of the households for 2018 in the last-ranked Bulgaria and Romania is 3585 euros and 3284 euros, respectively, and it is quite low for the whole considered period. When the income of the households is on the low degree, it is quite understandable that they will not invest in "green solutions." For example, investing in technologies for the use of renewable energy resources (such as, for example, geothermal energy) requires significant financial resources, but later, the operative costs are lower and these technologies enable producing of "clean" energy. This decreases the pressure on the nonrenewable resources; the GHG emissions are reduced and the sustainability goals are met. However, in the case when the income is quite modest, the less popular solutions regarding sustainability are often chosen.

With the main objective of defining the progress of the EU countries towards the SDGs, Mateusz et al. [50] applied the TOPSIS (Technique for Order Preference by Similarity) and VIKOR (Vlse Kriterijumska Optimizacija i Kompromisno Resenje) method. In the mentioned paper, Austria, Belgium, Germany, Denmark, Finland, Italy, and Luxembourg are in first place, while Bulgaria and Romania are in the last position among some other countries. For analyzing the improvements in the area of poverty in the EU, Piwowarski et al. [51] applied the TOPSIS method and VMCM (Vector Measure Construction) method. The finals results outlined Luxembourg, Finland, Austria, Malta, and Spain as the countries that have the best results towards reducing poverty. In the mentioned case, Romania and Bulgaria are in last place, again. To estimate the achieving of the sustainable development goals, Martín and Carnero [52] applied the AHP (Analytical Hierarchy Process). The obtained ranking emphasizes Norway as a country with very high sustainability, while Sweden, Denmark, the United Kingdom, and the Netherlands achieved a high degree of sustainability. In this case, Romania and Bulgaria are again among the countries that are on the very low level regarding sustainability. By observation of the results obtained by other researchers, it is obvious that there are similarities with the results presented in this paper here. As can be seen, there are some overlaps between the results regarding the first- as well as the last- positioned countries.

Finally, it can be concluded that the applied methodology is fully adequate and that the obtained results are real and justified, which confirms the stated hypothesis at the beginning of the paper. For the purpose of this paper, the combination of the Shannon Entropy and CoCoSo methods was used. The Shannon Entropy was applied for determination of the criteria weights, i.e., significance of the considered indicators. The main reason for the application of the Shannon Entropy relies in its objectivity, which enables minimizing the subjectivity onto the lowest level. The final ranking of the EU countries is performed by using the CoCoSo method, which is applicable and easy to use. Results obtained in this way represents a compromise solution that acknowledges differences among the evaluation criteria. In that way, this avoids the situation of the better ranking of countries that have good achievements only relative to certain goals, while the others are quietly bad. This compromise solution gives the perspective about the balanced achievements of the countries that are assessed. Besides, the comparison with other proved MCDM methods verified the usefulness and reliability of the proposed method. Although some authors, such as, for example, Miola and Schiltz [53], stated that the position of the country strongly depends on the chosen methodology and indicators, it could not be denied that involving the SDG indicators in the appropriate decision model would contribute to having a clear picture about sustainability level achieved in the particular country and their position relative to the others.

The main constraint of this paper is connected to involving the data for only 17 indicators in the evaluation process. By taking into consideration all proposed indicators, the obtained results will be more robust and reliable. Besides, the estimation of the progress of the countries by each goal separately and set of indicators connected to it will enable gaining more realistic insight into the current situation in the field of sustainability, and it will contribute to better projection of future trends. Because the proposed methodology proved its usefulness in the area of the assessment of the achievements regarding sustainability, the preposition for future work involves conducting the assessment procedure based on the MCDM methods, considered goals and indicators, and targeted values. Introducing the targeted values in the assessment model will ensure acquiring of the objective results that will better illustrate the current position and progress towards desired goals and emphasize the possible shortcomings that should be resolved. Besides, the proposed model could be improved by fuzzy, grey. or neutrosophic extensions and for the determining of the weights of the criteria the objective-subjective approach could be implemented. Despite this, the model based on the Shannon Entropy and CoCoSo methods proved its applicability and proves to be very convenient for estimating the progress of the EU countries towards achieving requirements from the "Agenda 2030."

5. Conclusions

The main objective of this paper was to introduce a hybrid MCDM model based on the CoCoSo method and Shannon Entropy method as an aid which will contribute to the facilitation of the assessment of the progress towards achieving the SDGs. For that purpose, the application of the Shannon Entropy method for determination of the criteria weights and the CoCoSo method for the final ranking of the considered countries is proposed. The introduced methodology is based on the 17 indicators relative to the 17 SDGs. Although the greater number of indicators is introduced, the evaluation process is performed by using 17 of them, which represents the considered goals in the best way. In that way, the situation of the complex and extensive model, as well as the repeating of the indicators, is avoided.

The final results indicate Sweden as the country with the best performance according to sustainable development. The countries that have shown the worst results are Bulgaria and Romania. In order to achieve the sustainable goals, these two countries should perform serious work in many crucial areas. Comparison of the obtained results with that obtained by the other authors affirms the conclusions that are made. The final considerations are that the MCDM methods, in the present case Shannon Entropy and CoCoSo, are useful for the assessment of the progress of the countries towards SDGs and that obtained results are objective and actual.

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Becoming Carbon Neutral in Costa Rica to Be More Sustainable: An AHP Approach

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Abstract: We propose addressing an organization's adoption of an environmental certification as a multicriteria problem considering environmental sustainability as well as economic and strategic aspects. Our methodological approach uses the Analytical Hierarchy Process (AHP), which we use in an empirical application to analyze the adoption decision of several Costa Rican firms and institutions. Firstly, we select a set of economic, strategic, and environmental criteria that seem relevant for the organization's direction. We select these criteria according to our literature review and a series of face-to-face interviews with scholars and companies' managers. As an environmental certification, we focus on Carbon Neutral (CN), which is a domestic certification aimed at reducing or offsetting carbon emissions. For the sake of comparison, we also consider ISO 14001, which is a well-known international standard aimed at compliance with environmental norms. We conduct the AHP analysis using the answers given by 24 companies and institutions, which in aggregate terms, give CN a higher score than ISO 14001. This result is mainly due to the fact that CN ranks above ISO 14001 when attending to environmental sustainability, although ISO 14001 tends to be preferred in economic and strategic terms.

Keywords: Analytical Hierarchy Process (AHP); carbon neutral; ISO 14001; multicriteria; economic-strategic; environmental sustainability; Costa Rica

1. Introduction

The 2030 Agenda for Sustainable Development [1] established 17 Sustainable Development Goals (SDGs) as a roadmap to guarantee a more sustainable future and overcome some of the most urgent challenges of mankind. These challenges include social and economic problems such as poverty and inequality and environmental threats such as global warming and climate change [2]. By shifting from conventional, polluting patterns to cleaner and more sustainable ones, companies can play a crucial role to achieve the SDGs, especially some of them such as providing affordable and clean energy (SDG 7), decent work and economic growth (SDG 8), ensuring sustainable consumption and production patterns (SDG 12) and fighting climate change and its impacts (SDG 13); see e.g., [3–5].

This change in companies' policies can involve adopting some voluntary environmental certification (VEC) or program (VEP). VECs and VEPs are non-mandatory approaches by which companies commit to improve their environmental standards in accordance with the specific requirements of each certification or program [6]. According to the OECD, these voluntary approaches "provide pragmatic responses to new policy problems, namely the need for more flexible ways to achieve sustainability, and the need to consider the rising concerns about industrial competitiveness and the increasing administrative burden" [7]. Moreover, it can be argued that VECs and VEPs are win-win approaches for companies and for society, because they improve the environmental performance of firms, while yielding them some economic and strategic benefits such as improving their competitiveness [8–10].

There is a wide variety of VECs and VEPs available for companies. Choosing one or some of them can be a complex task for business managers, since this decision will typically involve multiple criteria, including strategic, economic, environmental, or even ethical ones. The Analytical Hierarchy Process (AHP) can be a helpful tool to assist managers in taking certification decisions. AHP was developed by Saaty [11] and has become one of the most used methods, both in the public and the private sector, for making decisions that involve multiple criteria.

In business, AHP is typically used in contexts of uncertainty that require evaluating different alternatives based on qualitative and quantitative criteria. For example, Chin et al. [12] used AHP to rank success factors and develop strategies to implement an Environmental Management System (EMS) in Hong Kong manufacturing companies, as well as to decide whether to implement ISO 14001. Also in Hong Kong, Pun and Hui [13] investigated the companies' criteria, sub-criteria and benefits of implementing ISO 14001. Mathiyazhagan et al. [14] used AHP in combination with experts' opinions to rank the pressures to adopt Green Supply Chain Management in the Indian mining and mineral industry. In the same country and sector, Shen et al. [15] evaluated the relative importance of social, economic, and environmental criteria of green supply chain management. Cuadrado et al. [16] ranked the main factors involved in the construction of an industrial building in Europe. Ho et al. [17] used AHP to determine the importance of the barriers faced by electrical and electronics manufacturing companies in Malaysia when implementing material efficiency strategies. Thanki et al. [18] evaluated the influence of lean and green paradigms on the overall performance of small and medium enterprises. Malik et al. [19] applied AHP to evaluate the environmental performance of healthcare suppliers in the United Arab Emirates. Wang et al. [20] calculated the effect of the technical measures implemented in the tobacco industry for energy conservation and emissions reduction. Karaman and Akman [21] applied AHP to identify key criteria and sub-criteria of a Corporate Social Responsibility program in the airline industry.

In this study, we use AHP to evaluate the preferences of firms when choosing between different VECs and, ultimately, the propensity of the same firms to choose a specific VEC. We apply our proposal to the selection of an environmental certification in a group of Costa Rican firms and public institutions. Costa Rica is considered an international leader in terms of environmental sustainability, especially in forest conservation and the reduction of the Greenhouse Gas (GHG) footprint [22]. Different public and private environmental approaches contributed to improve the environmental quality and green image of Costa Rican companies and the country itself [23–28].

The Carbon Neutrality Program is a recent public initiative looking for a cleaner economy in Costa Rica. After measuring their carbon emissions and reducing or offsetting them, participating organizations can obtain a Carbon Neutral (CN) certification [29–31]. We are interested in finding out the managers' preferences and criteria that determine their decision to take part in this program. For the sake of comparison, we consider an alternative certification, namely ISO 14001, which is a well-known international standard.

The first methodological aim of our study is to establish a relevant set of criteria that firms and institutions consider when choosing an environmental certification. To do so, we perform three preliminary steps, which include an exhaustive bibliographic review, a series of in-depth face-to-face interviews with 11 managers of certified companies and a discussion with two scholars, experts in the field. As a result, we come up with a selection of criteria that we group in two blocks: environmental sustainability and economic-strategic factors.

Then, we use the AHP methodology with a double purpose: first, to measure the weights given by Costa Rican firms and institutions to the relevant criteria. Second, we evaluate how firms perceive the CN certification versus ISO 14001 in terms of those criteria. We apply AHP by conducting an e-mail survey that was successfully completed by 22 company managers and two managers of public institutions.

The remainder of the paper has the following structure: The following section provides a background of the certifications and the relevant criteria to evaluate them according to the previous literature. Section 3 presents the methodological steps that we followed in our research. Section 4 shows our results and provides some discussion. Finally, Section 5 concludes the paper.

2. Background

In this section, we review the main aspects of the two certifications under study, CN and ISO 14001, and the main criteria identified in the literature regarding firms' selection of environmental certifications.

The CN Program was introduced in Costa Rica in 2012 as a policy instrument in accordance with the government strategy to have a zero-carbon economy in 2050 [22,26,32]. The program began with the participation of two companies and currently involves around 84 organizations [29]. This program requires participants first to create GHG emissions inventories, and second, to build strategies to cut down, capture or offset those emissions. An auditing agency must verify both the inventories and the veracity of the reduction and offset strategies. All this information is corroborated by the Climate Change Department of the Costa Rican Government, which gives to the companies the "Carbon Neutral Declaration or Certification" [30,31].

ISO 14001 is an international environmental standard for companies that want to implement or improve an EMS. The number of worldwide ISO 14001 certified firms increased by 134% between 2007 and 2017. In the case of Costa Rica, 119 organizations were certified in 2017, showing a 18% growth in 10 years [33]. The aim of ISO 14001 is to help organizations improve their environmental performance in different dimensions. These include creating and putting into operation an EMS, with objectives, policies, and assignment of responsibilities within the firm to comply with them, generating some corrective and preventive actions in order to reduce the polluting emissions of the company and complying with national environmental laws [34].

We conducted a literature review about the criteria related to environmental aspects that companies consider when adopting different VECs and VEPs (not only those under consideration in our study). We grouped these criteria in two blocks: first, those related to environmental sustainability and, second, those associated with economic and strategic aspects.

Regarding environmental sustainability, there are two broad elements that are explicitly or implicitly present in most of the previous studies, namely the reduction in the use of materials and energy [13–16,18,19,21,35–39] and the reduction in the company's emissions [13,15,16,18–21,35–39].

Regarding economic and strategic aspects, the most frequently reported ones include improving the green image of the firm [6,14,40–50], increasing market shares or prices [6,14,42,49–56], saving production costs or increasing productivity [41–45,49,51,55,57–60], improving the company's relationship with stakeholders [6,42,51,57,59,61], adapting to mandatory regulations [6,45] and imitating the strategy of competitors [45,51]. In addition, managers also consider the costs related to the certification [12,45,46,48,51,62–65].

3. Materials and Methods

3.1. In-Depth Face-To-Face Interviews with Firms' Managers and Scholar Experts

To complement the conclusions obtained in our literature review and get a more detailed vision of firms' motivations to adopt VECs and VEPs, we conducted several in-depth face-to-face interviews with two groups of experts. Firstly, we interviewed 11 managers in charge of the environmental certification process in some Costa Rican companies (see Appendix A, Table A1). The interviews were not structured, i.e., we allowed for feedback comments during the interviews. This approach provided us some first-hand knowledge about the companies' reasons to adopt VECs.

Secondly, as a further validation, we also consulted two academic experts of the Faculty of Economic and Business Sciences at the Complutense University of Madrid, namely Gregorio Martín-de-Castro and Javier Amores-Salvadó. The aim of this discussion was to come up with a set of criteria that was representative enough of the relevant criteria, but not extremely large and detailed to make it manageable and easy to be handled by our survey respondents.

3.2. Questionnaire and AHP Application

Table 1 displays the set of criteria that we selected based on the literature review, the interviews to the managers and the academic experts' advice. We used these criteria to elaborate the questionnaire four our AHP application.

Table 1. Criteria included in the AHP questionnaire.

Economic-Strategic (E)	**Environmental Sustainability (S)**
Improving green image, public visibility and social legitimacy of the company (E_1). Increasing sales, market shares or prices (E_2) * Saving production costs or increasing productivity (E_3). Cost of the certification and investment in clean technologies (E_4).	Materials and energy use reductions during the production and distribution (S_1). Reduction in the amount and damage of emissions (gas, solid and water) generated by the company (S_2).

Note: * Since public institutions do not have a profit motive, we reformulate sub-criterion E_2 for them as "the possible improvements in the quality of the services offered and the increase in user satisfaction."

We have a double purpose: first, to evaluate the perception of a group of Costa Rican firms and public institutions with respect to the selected criteria and, second, to measure the propensity of those organizations to adopt a specific environmental certification according to this set of criteria. Among all the available certifications, this study focusses on CN for its relevance for the sake of pursuing sustainability in Costa Rica. As an alternative, we take ISO 14001, which as an important and well-established certification oriented to the EMS of the company.

We conducted a four-level-AHP exercise as shown in Figure 1. The first level ("*Goal*") is the organization's objective to choose an environmental certification. The second level refers to the general-purpose criteria (or simply "*Criteria*") that we consider relevant for the decision. According to our classification, these are the economic-strategic aspects, on the one hand, and environmental sustainability, on the one hand. The third level ("*Sub-criteria*") disaggregates the general-purpose criteria into more specific aspects. We refer to the latter as "sub-criteria" to differentiate them form the aggregate "criteria" on the second level. The lower level ("*Alternatives*") refers to the environment certifications that the respondents will evaluate in terms of the criteria and sub-criteria.

To conduct the exercise, we identified a group of companies holding the CN certification, the ISO 14001 certification, or both. For the sake of completeness, we also included some companies that did not hold any of them. Apart from companies, we also addressed some public institutions to check if the latter had somewhat different perceptions and preferences than the former. We identified the CN companies and institutions from the Climate Change Department [29] and the ISO 14001 organizations from the Institute of Technical Standards of Costa Rica [66]. In the case of non-certified companies, we searched the emails' contacts on their webpages.

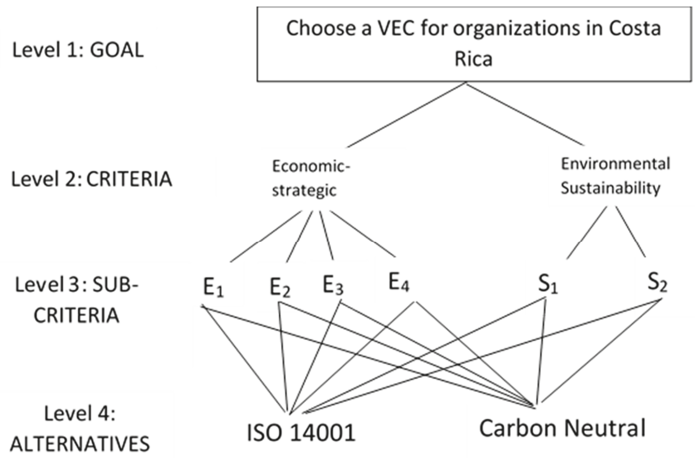

Figure 1. Analytic hierarchy structure of the study.

In 24 May 2019, we invited 171 companies and 12 certified public institutions to complete the questionnaire on the Google's survey platform. In the group of companies, 58 of them did not have the CN or ISO 14001 certification, 62 were CN but not ISO 14001 certified, 33 were 14001 but not CN certified and 18 had both certifications. With respect to public institutions, six of them were CN certified, 2 were ISO 14001 certified and four did not have any of both certifications.

In October 2019, 22 companies 'managers had completed the questionnaire correctly; four of them were CN certified, four ISO 14001 certified, seven had both certifications and seven had neither. In addition, two respondents were from public institutions (a university and a governmental department), both of which were CN but not ISO 14001 certified. Appendix A Table A2 lists the organizations' features and the positions of the respondents.

Following standard AHP methodology, the questionnaire sets pairwise comparisons of elements (criteria, sub-criteria, or alternatives) belonging to the same level with respect to their contribution to the immediate superior level. It is based on Satty's [11,67] scale, which allows us to convert the qualitative judgments into numerical values (see Table 2).

Table 2. Saaty's scale of preference between two elements.

Numerical Values	Definition	Explanation
1	Equal	Two elements contribute equally to the objective
3	Moderate	Experience and judgment slightly favor one aspect over another
5	Strongly	Experience and judgment strongly or essentially favor one aspect over another
7	Very strongly	An aspect is strongly favored over another and its dominance demonstrated in practice
9	Extremely	The evidence favoring one aspect over another is of the highest degree possible for affirmation
2, 4, 6, 8	Intermediate values	Used to represent a compromise between preferences listed above

Source: Saaty [11].

At the beginning of the questionnaire, we explained the structure of the questions and the Saaty scale. Then, we asked the respondents for their pairwise judgments within each level of the study, i.e., about the importance level of criteria (with respect to the goal of selecting a VEC), sub-criteria (with respect to each of the general criteria) and the relative merit of the alternatives, CN and ISO 14001 (with respect to each of the sub-criteria). Figure 2 shows three examples of the questions presented to the managers for levels 2, 3, and 4. The rest of questions had the same structure.

Comparing between criteria (level 2): Consider that we group all the aspects that concern your company or public institution in two blocks, putting on a balance, on the one hand, all the ECONOMIC-STRATEGIC aspects and, on the other, all those that have to do with ENVIRONMENTAL SUSTAINABILITY. Between these two blocks, which one do you think is more important for the company when choosing an environmental certification?

- O Economic-strategic criteria
- O Environmental sustainability criteria
- O Both groups of criteria have the same importance for the company or institution (if you chose this option, then check 1 in the next question)

Compare the above criteria using the scale ranging from 1 to 9

	1	2	3	4	5	6	7	8	9	
Both are equally important	O	O	O	O	O	O	O	O	O	The criteria chosen by you are extremely more important

Comparing between sub-criteria (level 3): Which of the following two sub-criteria is more important for your company when choosing an environmental certification?

- O Increasing sales, market shares or prices
- O Improving green image, public visibility and social legitimacy
- O Both sub-criteria have the same importance (if you chose this option, then check 1 in the next question)

Compare the above sub-criteria using the scale ranging from 1 to 9

	1	2	3	4	5	6	7	8	9	
Both are equally important	O	O	O	O	O	O	O	O	O	The criteria chosen by you are extremely more important

Evaluating alternatives (level 4): Which of the following environmental certifications do you think can contribute more to reduce the amount and damage of emissions produced your company or institution?

- O ISO 14001
- O Carbon Neutral
- O Both certifications contribute to the same extent (if you chose this option, then check 1 in the next question)

Compare both certifications regarding their contribution to the mentioned sub-criterion

	1	2	3	4	5	6	7	8	9	
Both contribute equally	O	O	O	O	O	O	O	O	O	The chosen certification contributes extremely more than the other

Figure 2. Three examples of questions used in the questionnaire to compare criteria (level 2), sub-criteria (level 3) and alternatives (level 4).

The individual responses give rise to the individual Satty's comparison matrices. Then, we use the geometric mean to combine the individual matrices and obtain the consensus pairwise comparison matrices [67–69]. These combined matrices are the ones that we use to compute the consensus priority weights for each level of the study, first for the whole group of respondents, and then to different subgroups (see Sections 4.1 and 4.2 below). Before computing the priority weights, we computed the consistency ratios (CR) of each of the relevant consensus comparison matrices. The consistency ratio is defined as $CR = CI/RI$, where CI is the consistency index of each matrix and RI is the consistency index of a random matrix of the same size. See Saaty [11,67] for details about the calculation of the consistency indexes (CI) and the average consistency values (RI) of randomly generated matrices. The consistency ratios of all the consensus comparison matrices that we use in the study (for the whole group and the subgroups) are well below 0.10, which is the threshold value recommended by Saaty [11,12,19,67].

We calculated the priority weights for the criteria, sub-criteria and alternatives using a variant of the traditional eigenvector method. For each level, we multiply the associated comparison matrix iteratively by itself. In each iteration, we add up the elements of each row of the matrix and normalize the resulting vector yielding an approximation to the first eigenvector of the initial matrix [70]. The process stops when the approximate eigenvector obtained in one iteration does not change significantly (up to four decimal places) from the previous iteration. The result is taken as the vector of relative importance or priority weights; see e.g., [71,72].

We denote the criteria eigenvector (level 2) as V_C. It indicates the weights or relative importance of economic-strategic and environmental sustainability criteria. In level 3, we have two eigenvectors: One for the economic-strategic sub-criteria, denoted as V_{EC}, and one for the environmental sustainability sub-criteria, denoted as V_{SC}. By combining levels 2 and 3 we can obtain the eigenvectors representing the global contributions of each sub-criterion to the goal of the study. Thus, the global eigenvector associated with the economic-strategic sub-criteria (V_{GEC}) is obtained as follows: $V_{GEC} = V_{EC} \cdot w_e$, where w_e is the weight given to the economic-strategic criterion in level 2, i.e., the first element of V_C. Similarly, the global eigenvector of all the sustainability sub-criteria (V_{GSC}) is obtained as follows: $V_{GSC} = V_{SC} \cdot w_s$, where w_s is the weight given to the environmental sustainability criterion (the second element of V_C).

At level 4, we have six two-components eigenvectors, V_{Ai} (i = 1, ... , 6), each of one indicates the weight or relative score of the alternatives in terms of a given sub-criterion. Specifically, we get four eigenvectors related to the economic-strategic sub-criteria that can be grouped as $V_{AE} = [V_{AE1}, V_{AE2}, V_{AE3}, V_{AE4}]$ and 2 eigenvectors related to the environmental sustainability sub-criteria, $V_{AS} = [V_{AS1}, V_{AS2}]$. We can order the alternatives according only to the economic-strategic criteria by computing $W_{AE} = V_{EC} \cdot V_{AE}$ or only to the environmental sustainability criteria by computing $W_{AS} = V_{SC} \cdot V_{AS}$. Finally, the globally preferred alternative can be determined by computing the global weight vector as follows: $W_{GA} = [V_{GEC} \cdot V_{AE}] + [V_{GSC} \cdot V_{AS}]$.

4. Results and Discussion

4.1. Overall Results

As a first approximation, we take the results arising from the combined answers of all 24 respondents, as shown in Table 3. At level 2, the participants considered, on average, that the economic-strategic criterion is more important (with a relative weight of 0.6) than environmental sustainability (0.4) when adopting a VEC.

Table 3. Priority weights by level (criteria, sub-criteria, and alternatives). All respondents (n = 24).

Criteria	V_c	Sub-Criteria	V_{EC} and V_{SC}	V_{GEC} and V_{GSC}	Comparing Alternatives (V_{Ai})	
					ISO 14001	CN
Economics-strategic (E_i)	w_e 0.6001	E_1	0.2911	0.1747	0.4478	0.5522
		E_2	0.2292	0.1376	0.6491	0.3501
		E_3	0.2950	0.1770	0.5849	0.4151
		E_4	0.1847	0.1108	0.4355	0.5645
Environmental sustainability (S_i)	w_s 0.3999	S_1	0.5207	0.2082	0.4863	0.5137
		S_2	0.4793	0.1917	0.2581	0.7419

Note: The question regarding the comparison of alternatives in terms of sub-criterion E_4 was answered by 23 respondents.

Regarding level 3, it is illustrative to compare the different sub-criteria related to economic and strategic aspects among themselves and do the same with the two sub-criteria related to environmental sustainability. Regarding economic-strategic aspects, saving production costs or increasing productivity (sub-criterion E_3) and improving green image, public visibility and social legitimacy of the company or the public institution (E_1) turn out to be the most important ones. Similar conclusions were found in previous studies about companies' motivations to adopt environmental certifications in Europe [41,43–45,47,58,61], North America [43,48,51], and Latin-America [40,46].

On the environmental side, the respondents consider that sub-criterion S_1, related to materials and energy use reductions during the production and distribution processes is slightly more important than S_2, which refers to reducing the amount and damage of emissions generated by the company (relative weights 0.52 vs. 0.48). The same or similar motivations were identified in previous studies applied to European [16,21,35,36], Asian [13–15,17–19,21,38], and American [36,37] companies.

When comparing the alternatives (certifications) according to each sub-criterion at level 4, we observe that CN is preferred under sub-criteria E_1, E_4, S_1 and S_2, but ISO 14001 is preferred under E_2 and E_3. Thus, as is typically the case in any multicriteria decision problem, our decision problem involves some degree of conflict in the sense that by adopting a specific certification, it is unlikely to get the best possible result in all the (sub) criteria at the same time.

In Table 4 we show the results of evaluating the alternatives, first, in terms of the economic-strategic criterion (and, implicitly, the associated sub-criteria), second, in terms of the environmental sustainability criterion (and sub-criteria) and, finally, combining both. It turns out that ISO 14001 is preferred to CN when considering only the economic-strategic criterion (0.53 vs. 0.47). On the contrary, CN is preferred to ISO 14001 in terms of the environmental sustainability aspects (0.62 vs. 0.38). When considering both criteria (and all the corresponding sub-criteria), CN turns out to be preferred to ISO 14001 (0.53 vs. 0.47).

Table 4. Choosing an alternative according to the criteria. All respondents (n = 24).

Alternatives	According to Each Criterion		According to Global Weights		
	W_{AE}	W_{AS}	$V_{GEC} \times V_{AE}$	$V_{GSC} \times V_{AS}$	W_{GA}
CN	0.4679	0.6231	0.2808	0.2492	0.5300
ISO 14001	0.5321	0.3769	0.3193	0.1507	0.4700
Total	1	1	0.6001	0.3999	1

A general reflection about these results has to do with the current relevance of environmental criteria in the organizations' decision-making process. In our case, considering environmental sustainability makes organizations, in aggregate terms, more prone to adopt CN rather than ISO 14001, although the latter is the preferred option when considering only economic and strategic aspects. This is the case even though the respondents place a larger weight on the economic-strategic criterion. The reason for this is that the respondents perceive CN as clearly preferred to ISO 14001 in environmental terms while the advantage of ISO 14001 over CN in economic-strategic terms is not so pronounced. This conclusion is in line with previous studies in the literature reporting that ethical and environmental concerns beyond purely economic motivations are becoming increasingly relevant in corporate decision-making; see e.g., [42,44,50,58,61,63,73].

4.2. Differences Across Groups

In this section, we split the group of respondents in five mutually exclusive sub-groups to explore how different they are in terms of their perceptions and preferences as regards criteria, sub-criteria, and alternatives. The groups are the following:

(i) Non-certified firms: Companies that are not CN nor ISO 14001 certified (n = 7),
(ii) CN firms: Companies that are CN but not ISO 14001 certified (n = 4),
(iii) ISO 14001 firms: Companies that are ISO 14001 but not CN certified (n = 4),
(iv) Companies that are CN and ISO 14001 certified (n = 7),
(v) Public institutions (n = 2), which include a university and a governmental department. Both are CN but not ISO 14001 certified.

4.2.1. Relative Importance of the Criteria and Sub-Criteria

Figure 3 illustrates the average weights given by the different groups to the general criteria (level 2). Notice that there are no differences between the weights given by "CN" and "ISO 14001" firms, both of which declare to consider both criteria equally important.

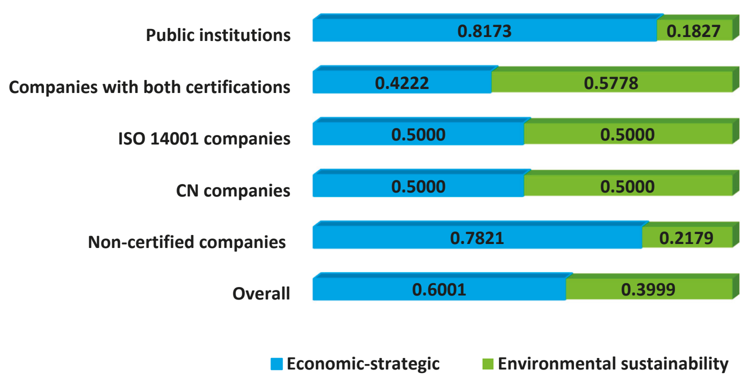

Figure 3. Weights' vector of criteria by respondents' subgroup.

The only group that gave larger importance to environmental sustainability (0.58) than to the economic-strategic criterion (0.42) is the one of firms that hold both certifications. This contrasts with firms without any of the certifications, which consider the economic-strategic criterion, by far, the most important one. We can interpret this difference as the former group being more concerned with sustainability, which is consistent with their decision to adopt more than one certification. As noted above, it was reported that ethical and environmental concerns are becoming more and more relevant for practical decisions in companies. In our respondents, this feature is particularly visible in the groups of certified companies, while the group of non-certified ones seem to be more concerned about more traditional, economic, and strategic factors. Inevitably, such priorities are institution-specific. Probably, if the answers were from other entities such as the Ministry of Tourism or Environment, the answers would be different, but those institutions were not among our respondents.

It is not so intuitive that the respondents belonging to public institutions constitute the group that give more importance to economic-strategic issues and less to environmental sustainability. One possible explanation for this fact is the existence of important legal and administrative barriers and rigidities in the management process of those institutions. Each of the consulted public entities has a delineated annual budget under which it must meet strategically defined and evaluated objectives [74]. Thus, they may consider environmental sustainability a complement rather than their central target, as they have other defined priorities, which are probably more directly linked to economic and strategic aspects.

Moving to level 3, Figure 4 shows the weights given by different groups to the economic-strategic sub-criteria. This comparison reveals that "public institutions" is clearly the group that gives larger importance to sub-criterion E_1 (improving the green image, public visibility, and social legitimacy of the organization), with nearly half of the total weight within the economic-strategic sub-criteria. It is also the most important one for companies holding the ISO 14001 certification (either alone or jointly with CN), although the difference with other sub-criteria is not so pronounced.

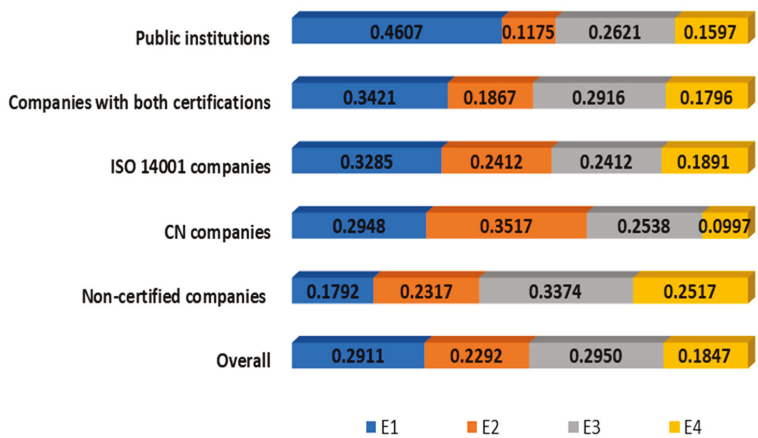

Figure 4. Weights' vector of economic-strategic criteria by respondents' subgroup. Note. For public institutions, we present sub-criterion E_2 as "the possible improvements in the quality of the services offered and the increase in user satisfaction".

It is also revealing that "non-certified companies" is the group that gives greater importance to sub-criteria E_3 (saving production costs or increasing productivity) and E_4 (the cost of certification and investment in clean technologies). These results seem consistent with their decision of not adopting any of the alternatives, which we can naturally understand as the result of a traditional and purely economic cost-benefit analysis.

Once again, CN and ISO 14001 companies are not very different regarding their assessment of economic and strategic criteria, although it is noticeable that the CN group seems particularly concerned about "increasing sales, market shares or prices" (E_2) and, on the other hand, they attach the smallest importance to the sub-criterion associated with costs (E_4).

Regarding the sub-criteria related to environmental sustainability (see Figure 5), those companies holding the CN certification (either alone or together with ISO 14001) are the only ones that give more importance to "reduction in the amount and damage of emissions (gas, solid and water)" (S_2) than to saving materials and energy use (S_1). This is an expected result, since the CN certification requires the reduction and/or compensation of the GHG footprint of participating organizations [30]. We can argue that CN companies are more concerned about the current environmental threat of climate change [23], which is more directly linked to polluting emissions than to saving materials and energy. It may be surprising to some extent that the same result does not hold for the public institutions, which are also

CN certified. The explanation can be like the one given in level 2 regarding the rigidity of institutional targets and budgets.

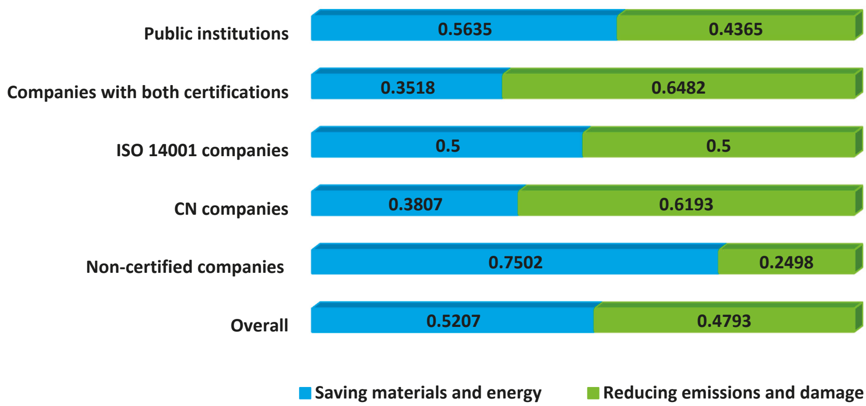

Figure 5. Weights' vector of environmental sustainability criteria by respondents' subgroup.

4.2.2. Choosing a Certification

At level 4, the two proposed certifications are evaluated in terms of the criteria and sub-criteria. Firstly, consider that the decision is made attending only at the economic-strategic criteria and sub-criteria. The results are shown in Figure 6. Consistent with their current behavior, CN companies and institutions consider that CN is preferable to ISO 14001 in economic-strategic terms. The rest of groups consider the opposite, although the differences in this respect are not very large.

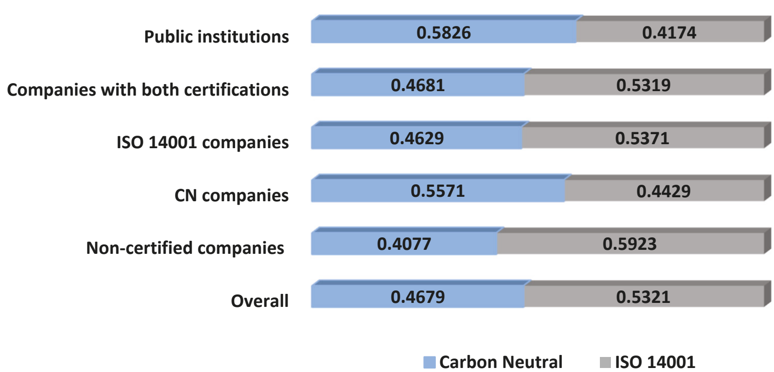

Figure 6. Deciding an alternative based on the economic-strategic criterion.

The situation is much clearer when we focus only on environmental sustainability (see Figure 7). All the groups consider that CN is clearly preferable to ISO 14001 except for the group of non-certified firms, which slightly consider the opposite. CN certification receives higher scores by all the sub-groups regarding S_2 (amount and damage of emissions), which is consistent with the nature of the CN program as it aims at reducing or offsetting the GHG footprint (see the evaluation of the alternatives according to each sub-criterion on Appendix A Table A3). Other expected associated benefits of this program include generating income to pay environmental services to farm owners who maintain forests or arboreal plantations. In addition to capturing carbon emissions, forests generate other environmental services such as biodiversity protection, watershed protection and scenic beauty [28].

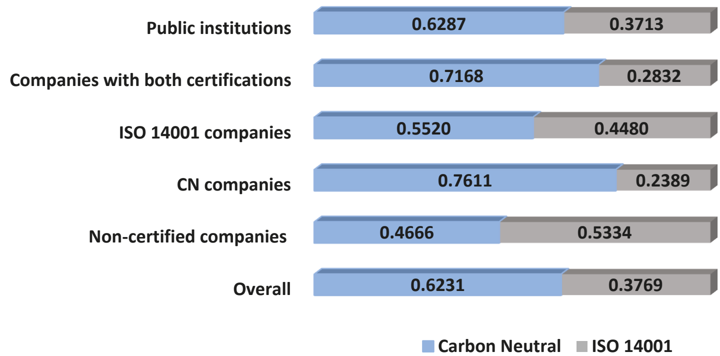

Figure 7. Deciding an alternative based on environmental sustainability criteria.

As expected, the relative valuation of the CN certification in environmental terms is particularly notable for those institutions and companies that are CN certified (either alone or together with ISO 14001).

Finally, by using the global weights of all the criteria and sub-criteria, we can determine the most preferred option, as shown in Figure 8. Except for the group of companies without any certification, CN always receives higher global scores than ISO 14001. As expected, CN is particularly well considered among those institutions and companies that already adopted it, which we can interpret as a proof of consistency between their reported preferences and their observed behavior. It is remarkable; anyway that even those companies that adopted only ISO 14001 also attach a marginally higher score to CN than ISO 14001 (roughly, 0.51 vs. 0.49). Although this is not a strong result, the fact that these firms do not give a higher score to the certification that they adopted is already a surprise.

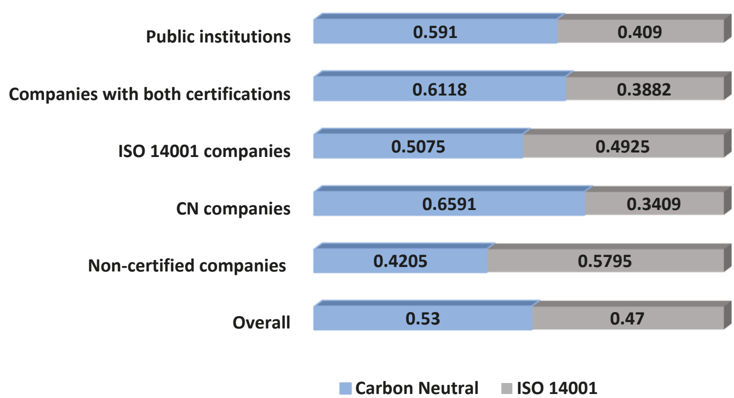

Figure 8. Deciding an alternative based on environmental sustainability and economic-strategic criteria.

This counterintuitive result merits some explanation. One partial reason is that on average, "ISO 14001" companies considered that CN certification was clearly preferable to ISO 14001 as regards sub-criterion *S2*, "amount and damage of emissions" (0.74 vs. 0.26), which has a reflection in the final score. Moreover, two of the companies in the ISO 14001 group obtained this certification more than 18 years ago, when climate change and carbon emissions were not considered to be important as they are today, and the CN program did not even exist. Our findings suggest that their certification decision would not be necessarily the same if they had to decide right now for the first time.

As a future extension of this analysis, it would be interesting to perform a more detailed analysis of how different firms' characteristics influence their preferences and propensity to adopt each certification. A statistically significant test would require a larger sample and is beyond the scope of this paper but, to have a glimpse, in Appendix A Figure A1 we show a preliminary approach by splitting our group of respondents, in two different ways: By size (large vs. small and medium, where "large" means more than 100 employees) and by sector (industry vs. services). The distinction in terms of size does not seem very relevant in qualitative terms in the sense that both groups of firms (large and small-medium) give a larger aggregate score to CN than ISO 14001 but, in quantitative terms, small and medium firms tend to have a more pronounced preference towards CN, while for larger companies there is almost a tie between both certifications. On the other hand, the activity sector seems to matter in qualitative terms since the service sector (where we included the relevant companies and the two public institutions in our sample) turns out to prefer CN while manufacturing companies give a higher score to ISO 14001 than to CN. Given the limited number of respondents and the possible interactions among different effects, these results should be taken with care, but they provide us with useful hints for future developments.

5. Conclusions

Both environmental sustainability and economic-strategic aspects appear to be important for Costa Rican organizations (firms and public institutions) when adopting an environmental certification. The group of firms and institutions that participated in our AHP study reported that on average, they consider the economic-strategic criterion more important than environmental sustainability. When considering both criteria with their corresponding weights, the CN certification is preferred, on average, to ISO14001. We can consider this result as a reflection of the increasing concern about climate change and the impulse given by the Costa Rican Government to the CN Program.

By splitting the respondents into groups, we find that the environmental sustainability criterion is the most important one only for firms that hold both CN and ISO 14001 certifications, which is consistent with their observed behavior.

In economic and strategic terms, ISO 14001 is considered superior to CN, except by those companies and institutions that are CN (and not ISO 14001) certified. On the other hand, the CN certification received, on average, a much higher score in terms of environmental sustainability by all groups of certified organizations and institutions (CN or ISO 14001). This clear preference under the environmental component makes CN be the preferred almost unanimously across different subgroup of respondents.

One central conclusion is that presently, environmental sustainability is becoming more and more relevant in managers' decisions. Considering this criterion apart from purely economic and strategic ones can lead them to implement deeper environmental improvements, such as carbon neutrality.

Although AHP is a decision methodology designed to rank alternatives and ultimately choosing among them, it is important to underline that the two certifications that we considered are not mutually exclusive. On the contrary, they could be complementary in improving the environmental performance of organizations.

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Appendix A

Table A1. Managers interviewed face-to-face in Costa Rica about companies' reasons to get environmental certifications.

Number of Interviewees *	Position	Activity	Environmental Certifications	Interview Day
1	MM	Industrial	CN, ISO 14001, EBF	09/09/2016
2	MM, EM	Financial	CN, ISO 14001	22/09/2016
2	CSRC, EM	Car Sales	CN, ISO 14001	13/09/2016
1	CSRC	Car Sales	CN, ISO 14001	16/08/2017
1	MM	Industrial	ISO 14001	11/08/2017
1	MM	Internal Audit	ISO 14001, EBF, OHAS 18000	17/08/2017
1	MM	Financial	CN, ISO 14001	18/08/2017
1	GM	Agricultural	Fairtrade, Eco-LOGICA, USDA organic	22/08/2017
1	GM	Travel agency	CST, CN, EBF	23/08/2017

Notes: GM-General Manager, MM—Management Manager, EM—Environmental Manager, CSRC—Corporate Social Responsibility Coordinator, CST—The Costa Rican Certification for Sustainable Tourism; CN-Carbon Neutral, EBF—Ecological Blue Flag. * The name of the interviewees and companies are omitted for the sake of anonymity.

Table A2. Position of the questionnaire respondents and companies' features.

Respondent Position	Activity	Size	Certifications	
			CN	**ISO 14001**
EM	Construction and building rental	L	Yes	Yes
EA	Energy	L	Yes	Yes
MM	Information and communication	L	Yes	Yes
MM	Pharmaceutical industry	L	Yes	Yes
EM	Finance	L	Yes	Yes
MM	Industrial	M	Yes	Yes
CSRC	Car Sales	L	Yes	Yes
MM	Education *	L	Yes	No
CSRC	Pension Fund Administration	L	Yes	No
Sub MM	Machinery sales	M	Yes	No
EM	Food Industry	M	Yes	No
HRM	Tourism Agency	M	Yes	No
EM	Government Department *	L	Yes	No
MM	Technology	L	No	Yes
EA	Food Industry	M	No	Yes
MMa	Industry	L	No	Yes
MM	Industry	M	No	Yes
GM	Food Industry	L	No	No
MMa	Consulting services	S	No	No
N.A.	Manufacture	M	No	No
MM	Commercialization	S	No	No
MM	Food Industry	M	No	No
GM	Food Industry	M	No	No
MM	Industry	L	No	No

Legend. *Position*: EA—Working into the environmental area, GM—General Manager, HRM—Human Resources Manager, MMa—Market Manager, MM—Management Manager, EM—Environmental Manager, CSRC—Corporate Social Responsibility Coordinator. *Size*: S-Small (fewer than five employees), M-Medium (between 6 and 100 employees), L-Large (more than 100 employees). * Public Institutions.

Table A3. Deciding an alternative based on different individual criteria.

Groups	Overall		Non-Certified Firms		CN Firms		ISO 14001 Firms		Firms with both Certifications		Public Institutions	
Sub Criteria	CN	ISO 14001	CN	ISO 14001	CN	ISO 14001	CN	ISO 14001	CN	ISO 14001	CN	ISO 14001
E_1	0.5522	0.4478	0.5397	0.4603	0.6271	0.3729	0.5319	0.4681	0.4442	0.5558	0.8093	0.1907
E_2	0.3509	0.6491	0.3290	0.6710	0.5432	0.4568	0.4633	0.5367	0.2643	0.7357	0.2052	0.7948
E_3	0.4151	0.5849	0.2901	0.7099	0.5114	0.4886	0.3660	0.6340	0.5895	0.4105	0.2240	0.7760
E_4	0.5645	0.4355	0.5439	0.4561	0.5157	0.4843	0.4663	0.5337	0.5285	0.4715	0.7948	0.2052
S_1	0.5137	0.4863	0.4091	0.5909	0.7180	0.2820	0.3660	0.6340	0.5832	0.4168	0.5000	0.5000
S_2	0.7419	0.2581	0.6392	0.3608	0.7876	0.2124	0.7380	0.2620	0.7893	0.2107	0.7948	0.2052

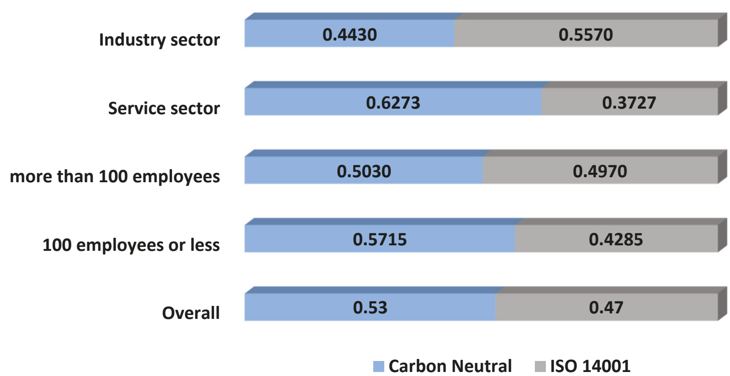

Figure A1. Deciding an alternative based on environmental sustainability and economic-strategic criteria. According to sector and size of the organizations.

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A Benefit–Cost Analysis of Food and Biodegradable Waste Treatment Alternatives: The Case of Oita City, Japan

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Abstract: As the generation of food scrap, kitchen, and biodegradable wastes increases, the proper handling of these wastes is becoming an increasingly significant concern for most cities in Japan. A substantial fraction of food and biodegradable waste (FBW) ends up in the incinerator. Therefore, an analytic hierarchy process (AHP) benefit–cost analysis technique was employed in this study to compare different FBW treatment technologies and select the most appropriate FBW disposal technology for Oita City. The four FBW treatment options considered were those recommended by the Japanese Food Waste Recycling Law: anaerobic digestion, compost, landfill, and incineration, which is currently in use. The fundamental AHP was separated into two hierarchy structures for benefit analysis and cost analysis. The criteria used in these two analyses were value added, safety, efficiency, and social benefits for benefit analysis, and cost of energy, cost of operation and maintenance, environmental constraints, and disamenity for cost analysis. The results showed that anaerobic digestion had the highest overall benefit while composting had the least cost overall. The benefit–cost ratio result showed that anaerobic digestion is the most suitable treatment alternative, followed by composting and incineration, with landfill being the least favored. The study recommends that composting could be combined with anaerobic digestion as an optimal FBW management option in Oita City.

Keywords: criteria; food and biodegradable waste; analytic hierarchy process; benefit–cost analysis; multi-criteria decision analysis; waste disposal technology; anaerobic digestion

1. Introduction

In the discourse of developing, analyzing, implementing, and optimizing frameworks for existing waste management systems in any city, the 2030 Agenda for Sustainable Development comes to mind. This agenda comprises 17 Sustainable Development Goals (SDGs) and 169 targets set as the defined requirements for achieving sustainable development by 2030, and a strategy for accomplishing sustainability [1]. Urban development and management in general brings many challenges to light. Cities can play an essential role in this regard by making human settlements habitable, sustainable, safe, and resilient (SDG 11), as well as by ensuring sustainable consumption and production patterns (SDG 12) in achieving the SDGs.

The considerable amounts of food scraps and decomposable waste generated within cities in Japan have resulted in controversial issues of substantial concern. The creation and effective management of these organic wastes are too much for the municipal and local authorities to be able to properly manage. These authorities are wrestling with substantial amounts of food and biodegradable waste (FBW), waste administration costs, and methods of treatment, as well as the potential impact of generated waste on the local environment [2]. Furthermore, issues such as funding and searching for the most suitable dumping equipment, wrongful disposal, conflicts concerning various areas across long hauls of waste, and concerns regarding unwanted disposal outcomes remain challenging [3,4].

Currently, there is an increasing demand for the proper integration of effective policies that aim at practicing sustainable waste management in the main waste stream [5–7]. To this end, the Japanese government legislated the Act on the Promotion of the Recycling of Recyclable Food Resources, titled the Food Recycling Act (the Sound Material-Cycle Society in the act mentions the Biomass Nippon Strategy) in 2001 and reviewed it in 2015 [5,6,8]. This act was enacted to champion the recycling of recyclable organic resources, primarily as feedstock for ethanolization and bio-gasification technologies [8]. Also included are waste preventative policies intended to reduce, reuse, and recycle the quantity of FBW collected by local authorities from households. Oita Prefecture is currently implementing these policies alongside the Oita Zero-Waste Strategy [9].

Oita is the capital of Oita Prefecture, with a projected populace of 479,466 people and 218,532 homes (as of 30 January 2018), and a density of 954.35 residents/km^2 [10,11]. The volume and handling methods of FBW and the inhabitants of Oita City are some of the reasons that this city was chosen for this research. In addition, this city is used as a reference point for the surrounding cities with similar conditions. At present, a total 21,976 t of food and kitchen waste is created monthly (38.6% of the total MSW), and almost 65% of the inhabitants are middle-income households [9,10]. FBW is sent directly to combustion, primarily managed by two incineration plants [11,12].

Despite the sound support in favor of material recycling and recovery, reinforced by legislation, incineration continues to serve as the chief and the predominant source of MSW in most cities in Japan [7,11–13]. FBW exerts a straightforward and substantial impact on the volume and structure of MSW, and constitutes the most sizable share mix with a low calorific value and high water content [14]. However, energy and combustion efficiency decrease whenever these wastes are incinerated [7,15–17].

Current findings have shown the incineration of FBW has raised concerns in terms of economic and ecological consequences (regarding the generation of greenhouse gases (GHG)) [18–20]. The investigation of food waste management systems by Bernstad and la Cour Jansen [16] highlighted that whenever support fuel (e.g., diesel) is used, it eliminates the encouragement aimed at material recycling as a result of insufficient thermal capacity in damp FBW. In addition, it hinders the use of other waste materials (plastics and paper), when they are utilized to increase the calorific capacity of composting [16]. Villanueva and Wenzel [21] argued that recycling of material is more profitable than incineration in terms of energy utilization and energy-related impacts. Following a comprehensive assessment of various recycling techniques used within Japan, Takata et al. [5] established that the cost and GHG emissions of FBW treatment equipment are below those of incineration facilities. Put differently, considerable attention should be focused on the specific type of waste treatment technology used and its potential impacts on the environment [22–24].

A full-scale investigation is required, because of the complexities of FBW management, to select the right FBW disposal method. Choosing the appropriate waste handling method will be helpful in mitigating negative ecological consequences, and will simultaneously save money and time. For this purpose, this study assessed the suitability of FBW treatment technology in Oita City, employing an analytic hierarchy process (AHP) benefit–cost analytical approach. The focus was on the FBW treatment methods endorsed in the Food Recycling Act, which include incineration with heat and electric energy recovery; landfill, which lacks any kind of energy retrieval; composting; and anaerobic digestion [7,8,25].

This study was based on the theoretical improvement and application of an incorporated food and biodegradable waste management system (FBWMS) to facilitate the ability to address cultural, economic, environmental, political, social, and technological concerns in sustainable waste management systems. The present FBWMS practices and the possibility of enhancing this current system through applying multi-criterion decision analysis (MCDA) were the core of this study. Therefore, the specific objectives of this study were to examine which waste treatment alternatives would be the least costly and the most beneficial options to treat the amount of FBW generated. Consequently, investigating the potential benefit and cost of FBW treatment facilities using Oita City as a case study will contribute to the value increase of incorporating FBW management within the framework of decision support (making) in the MSW administration system [2]. Recently, the application of MCDA techniques in tackling waste management challenges has been increasing. For this purpose, this study provides additional knowledge by demonstrating how an AHP benefit–cost analysis can be employed to settle waste management challenges.

2. The Application of Multi-Criteria Decision Analysis (MCDA)

AHP has been conceivably the most often applied MCDA technique in constructing and solving complex decisions by key decision-makers [26–33]. According to Belton and Steward [34], MCDA is an umbrella phrase utilized to characterize a compilation of established procedures that aims at examining the specific explanation of multiple criteria in supporting of both single and group decision-makers to execute informed decisions. In support of this, Babaloa [2] described MCDA as a functional apparatus for environmental evaluation wherein a complicated, interconnected, and wide range of ecological, socio-cultural, technical, economic, and monetary concerns are considered. In addition, where required tradeoffs between competing goals and standards are equally measured. MCDA provides a significant and straightforward decision-making framework that are primarily relevant to circumstances where a single criterion disappoints, and substantial environmental and societal consequences are impossible to monetized [35,36].

The flexible nature of MCDA makes it applicable at all stages of decision-making, from the consideration of project options to wider-rang of policy decisions [26,27]. The strong point of MCDA lies in the significant assessments of criteria that are not in monetary terms. On the contrary, they are regularly adjusted by means of weighing, scoring, and ranking with a more diverse spectrum of qualitative influences. [2,34,37]. For instance, various ecological and societal standards, maybe established in combination with monetary benefits and costs. Similarly, both financial and non-monetary goals may well affect policy decisions [2,34,37]. MCDA can be adapted to use judgements ideally aimed at problems with non-monetize criteria. Most often, it offers the possibility of an additional representation of tradeoffs to be made in the decision problem. Therefore, pairwise comparison is a predominantly used interactive approach to establish tradeoff relationships among key criteria [29,30].

This technique is considered for both qualitative and quantifiable terms during a realistic decision-making environment. It is beneficial in situations where decision-makers are confronted with difficulties when handling qualitative information [35,36,38]. The implementation of MCDA procedures to waste treatment challenges, in general, comprises the combination of cultural, economic, ecological, political, and societal principles in conjunction with the priorities of stakeholders while upsetting the difficulties in monetizing basically nonmonetary components [27,28,36,39–43]. A significant majority of these articles elaborate reasonable decision-making regarding waste management regulations through the examination of an extensive variety of potential impacts. These impacts are frequently not considered in economic analyses due to the lack of measurement in terms of monetary value [36].

The real-life applications of AHP techniques have been shown beyond doubt to be valuable decision-making tools. These applications have been grouped by Vaidya and Kumar [32] into the fields of choice, assessment, planning and development, allocations, priority and ranking, decision making, and benefit–cost analysis. Furthermore, Williams [44] proceeded to substantiate that the straightforwardness and the flexibility of AHP have naturally made it more universally applicable; as such, it is implemented in military, manufacturing, management, education, government, society, sports, personnel, engineering, and policymaking [32,45]. Consequently, this study employs the AHP based benefit–cost analysis to evaluate the optimum disposal technology for FBWM in Oita City, Japan. The illustrations of this technique have been presented by Anagnostopoulos [33], Ishizaka and Labib [45], Beria et al., [46], Wedley et al. [47], and Wedley et al [48].

The rationale for applying AHP based benefit–cost analysis in this study is based on its straightforwardness, familiarity, and flexibility. Most interesting is the merit of AHP in contrast to and in connection with other techniques of MCDA [31,45]. Apart from the merits of AHP, one of the shortcomings of the subjective nature of the process where decision makers cannot absolutely guarantee not mixing their decisions with personal opinions, feelings, and biases is of concern. In addition, more resources and time are needed when dealing with a large number of hierarchy levels in a complex decision-making process. As such, the number of pairwise comparisons depends on the hierarchy levels. Nonetheless, Huang et al. [49] emphasized that, regardless of what techniques of MCDA are applied, the choice is primarily subjected to the priority of the decision-maker. For this purpose, the practical implementation of this technique will be outlined in this study with the goal to assess the optimum disposal technology for FBWM in Oita City, Japan.

Regardless, AHP is suitable for measuring non-material criteria and assessing decisions in a multi-tiered hierarchy of goals regarding criteria, sub-criteria, and alternatives. The AHP benefit–cost approach primarily includes two hierarchies for the same set of objective or goal, one for benefit and the other for cost analysis [31,47,48]. Through pairwise comparisons of a set of criteria, the weights and composite priorities of the options are obtained for both the benefit and cost analyses. [47,48]. The resulting composting benefits and costs priorities are then compared to select the alternative with the highest ratio. In the case where the comparisons are inconsistent, Saaty offers a procedure for enhancing consistency [29–31]. The step-by-step analytical process in AHP proposed by Saaty & Vargas [31] is shown in Figure 1.

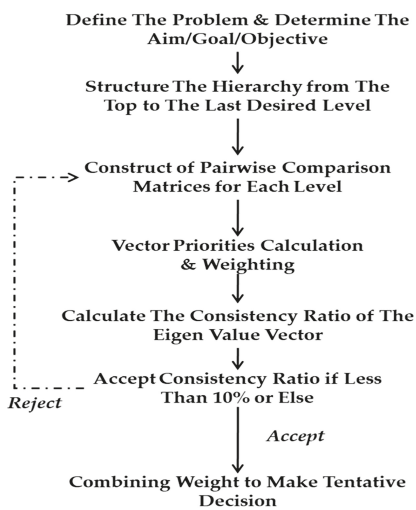

Figure 1. The Step-by-step analytical hierarchy process.

3. Materials and Methods

The AHP is founded on a distinct mathematical arrangement of eigenvectors and consistent matrixes to create relative weights needed to analyze alternatives or criteria with respect to a decisive judgment in a pairwise comparisons method [29,31]. According to Saaty [29], the AHP assists in dividing the main objective into smaller segments for the purpose of helping decision makers in priority assessment (subjective opinion). To start with, a goal is derived from the stated problem and constructed into a hierarchy structure (from low to high level) with the goal at the top-level. Underneath it, are the criteria, in some cases, sub-criteria as well as the options to be evaluated. However, pairwise comparison allows the analyst to focus on one comparison at a time by comparing among options for each criterion. The pairwise comparisons are transformed to a reciprocal comparison matrix. Inasmuch as the matrix is adequately reliable, equation 1 can be used to estimate the priority vector. The priority vector illustrates the relative weights among the criteria and options compared.

$$AW = \lambda_{max} W \quad (1)$$

where A is the comparison matrix, W is the priorities vector, and λ_{max} is the principal eigenvalue.

Since there is redundant or unnecessary information included in the comparison matrix it is necessary for the final result to be synthesis, with the intention of making the procedure less reliant on a single decision. The consistency ratio (CR) is measured (Equation (2)) to confirm the consistency of the judgments and, at the same time, serves as a feedback mechanism:

$$CR = \frac{CI}{RI} \quad (2)$$

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (3)$$

where CI is the consistency index; n is the number of the comparison matrix; and RI is the random consistency index for the n^{th} row matrixes of randomly generated pairwise comparisons. i.e. the RI value corresponding to the number of the comparison matrix (or number of criterion) is selected. For instance, if n is 4 the corresponding RI will be 0.9 and the average RI of 500 (sample size) matrices is illustrated in Table 1. Saaty highlighted that the CR should be 0.10 or less (<10%), otherwise there is a need to remodify the responses (subjective judgments) to reduce the inconsistency. For more studies on AHP, see Saaty [29,31].

Table 1. Random Consistency Index (RI).

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

3.1. Choosing the Utmost Appropriate FBW Treatment Alternative

A benefit–cost model based on the AHP approach is used to map out and evaluate the treatment option with the intention of conserving the residential environment and enhancing public health by the means of controlling the amount of waste generated, proper sorting, storage, collection, transport, recycling, and disposal [50]. The first step was to break down the structure into further sub objectives in the opposite direction and separate criteria within different hierarchy structures of benefit and cost. The rationale for this breakdown is to group criteria in a similar structure, and it is more comprehensible to compare in this case than in two opposite arrangements. In this aspect, the complete weights can be combined into one hierarchy. Initially, the relative priority of benefits and costs are calculated separately, afterward the overall priority of benefit analysis is divided by the cost analysis to produce the final result.

3.2. Definitions and Determination of the Goal

The intention of this empirical inquiry was to identify which FBW treatment technology is the utmost appropriate in handling the waste created in the city of Oita. The most suitable alternative concerning the goal was defined so that multiple, equally significant sub-objectives would be fulfilled. The increase of the combustion efficiency rate through the reduction of the quantity of FBW going to the incinerator thereby leads to a gradual reduction in local air pollution, environmental impact, and increase in renewable energy generation. The second substantial factor is the sustainable FBW treatment leading to integrated management of waste.

3.3. Clasification of Criteria and Alternatives into Hierarchy Structure

Significantly, all the objectives have to be well-defined with the purpose to outline and finalize these criteria. Literature and documents on the area under discussion, including the Food Recycling Act, were consulted. The preliminary criteria selected after carrying out analysis and revision on the Act were then combined with the objectives collected from literature [27,28,40–43,51–53]. In addition, the criteria used are adapted from Babalola's studies [2]. This was done with the purpose of discovering the most comprehensive, functioning, essential, and negligible variety of criteria to characterize diverse objectives [43].

The overall aim is to achieve or to choose the most appropriate FBW treatment facility as well as increasing the standard of FBWM to a sustainable practice. Separating the goal into sub-objectives can lead to finding more goals that can be presented about the current situation in Oita City. To bring this to simplicity, the number of various criteria and goals are structured according to the four main areas of concern, that are environmental, socio-cultural, technical, and economic. These lead to the facilitating and identifying of criteria listed below.

The cost analysis consists of four criteria listed below, which may have direct or indirect mandatory expenditure:

a. Cost of Energy
b. Cost of Operation & Maintenance
c. Environmental Constraints
d. Disruption/Disturbance/ Disamenity

The benefit criteria consist of those that might attain quantitative or qualitative benefits and four of these criteria were considered:

e. Value Added
f. Safety/Wellbeing/Reliability/Trustworthiness
g. Efficiency/Effectiveness
h. Social Benefits

It is crucial to determine the proper FBW treatment alternatives or options that can accomplish the goals and purposes of the research underline. The set of four alternatives, which was used in the AHP structure is based on the waste disposal type recommended by the Food Waste Recycle Law. The options are mentioned below:

i. Anaerobic Digestion
j. Incineration
k. Compost
l. Landfill

The backbone of the whole AHP approach is a logically structured hierarchy. Figures 2 and 3 show the two separate AHP structures for both benefit and cost analysis. The goals are to select the options with the least cost and the most significant benefits respectively. The first level identifies the goals, and the essential criteria at the second level are comprised of four criteria, whereas the last (third) level contains the options of FBW treatment. Both benefit and cost hierarchies have the same numbers of elements in all levels, except that at the criterion level are different criteria.

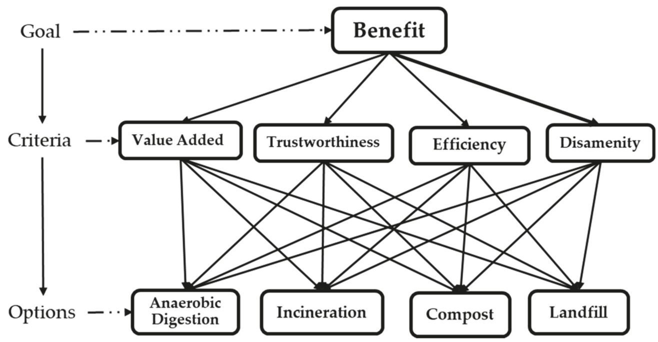

Figure 2. Hierarchy structure for benefit analysis.

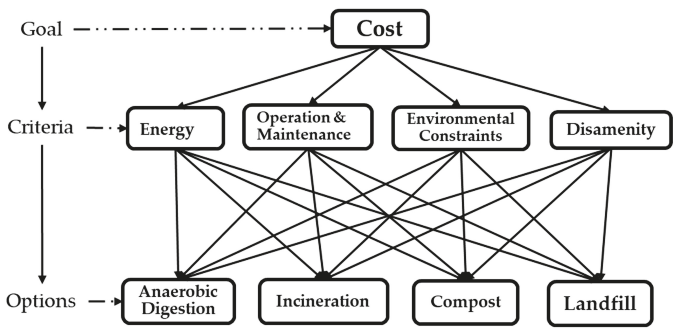

Figure 3. Hierarchy structure for cost analysis.

4. Results

4.1. Pairwise Comparison Matrix (PCM) and Weighting of Criteria

Fundamentally, there are two methods used when assigning weights or judgment to criteria. They are group opinion (consensus experts/decision-makers) and single opinion (decision-maker/author's judgment) [29,30,51]. In theory, no difference in their practical application provided the value of the outcome can be examined by how consistently satisfactory the findings [29]. In each instance, the pairwise comparison judgments are made with each essential factor (in a specified hierarchy structure) in connection with the other component at an equal status. Present study uses the single judgment procedure in conjunction with MSW management regulation and policy in Japan. A separate criterion for both benefit and cost analyses (Figures 2 and 3) used in the computing process were split into three key levels. Level one represents the goal, level two is the criteria, while the final standard is the FBW treatment options.

The relative preference of the judgment made for each pairwise comparison is measured in accordance with the 1–9-point scale of preference (Table 2) introduced by Saaty [29,31]. The pairwise comparison of one set of elements at a time is the downside of applying this scale. Comparisons are performed by matching two elements based on the 1–9-point preference scale to indicate how many times more important one factor is over another simultaneously satisfying the reciprocal condition [29,31]. For example, in Table 3, if the Value Added criterion is four times as important (preferable) as the Safety criterion, it implies that Safety is one quarter as preferable as Value Added.

Table 2. Saaty's pairwise comparison scale.

Numeric Intensity	Verbal Judgement
9	Extremely favored
8	Very strongly to extremely
7	Very strongly favored
6	Strongly to very strongly
5	Strongly favored
4	Moderately to strongly
3	Moderately favored
2	Equally to moderately
1	Equally favored

Table 3. Pairwise comparison matrix of criteria for benefit.

Criteria/Options	Value Added	Safety	Efficiency	Social Benefits	Priority Vector
Value Added	1	4	5	1	0.4101
Safety	1/4	1	3	1/4	0.1390
Efficiency	1/5	1/3	1	1/3	0.0824
Social Benefits	1	4	3	1	0.3685

Note: λmax = 4.2430, Consistency Index (*CI*) = 0.0810, Consistency Ratio (*CR*) = 0.09 < 0.1.

The pairwise comparison matrix consists of a total of five tables, each for the benefit and cost analysis and they are presented in Tables 3–8 and Tables 10–15 correspondingly. Table 3 and Table 10 represent the goal criteria, while the remaining denotes the connection of the four alternatives to the "criteria concerned" at all levels. Since all comparisons have less than a 1% consistency ratio, it is reasonable to conclude that the weights used are reliable and consistent.

Table 4. Pairwise comparison matrix of the alternatives for value added.

Options	Anaerobic Digestion	Incineration	Compost	Landfill	Priority
Anaerobic Digestion	1	3	7	9	0.5782
Incineration	1/3	1	5	7	0.2948
Compost	1/7	1/5	1	2	0.0788
Landfill	1/9	1/7	1/2	1	0.0481

Note: λmax = 4.1771, *CI* = 0.0590, *CR* = 0.066 < 0.1.

Table 5. Pairwise comparison matrix of the alternatives for safety.

Options	Anaerobic Digestion	Incineration	Compost	Landfill	Priority
Anaerobic Digestion	1	3	1/2	5	0.3050
Incineration	1/3	1	1/4	4	0.1490
Compost	2	4	1	6	0.4869
Landfill	1/5	1/4	1/6	1	0.0591

Note: λmax = 4.1856, *CI* = 0.0619, *CR* = 0.069 < 0.1.

Table 6. Pairwise comparison matrix of the alternatives for efficiency.

Options	Anaerobic Digestion	Incineration	Compost	Landfill	Priority
Anaerobic Digestion	1	3	2	7	0.4656
Incineration	1/3	1	1/3	5	0.1665
Compost	1/2	3	1	6	0.3178
Landfill	1/7	1/5	1/6	1	0.0501

Note: λmax = 4.1827, *CI* = 0.0609, *CR* = 0.068 < 0.1.

Table 7. Pairwise comparison matrix of the alternatives for social benefits.

Options	Anaerobic Digestion	Incineration	Compost	Landfill	Priority
Anaerobic Digestion	1	1	5	7	0.4166
Incineration	1	1	5	7	0.4166
Compost	1/5	1/5	1	4	0.1175
Landfill	1/7	1/7	1/4	1	0.0492

Note: $\lambda max = 4.2093$, $CI = 0.0698$, $CR = 0.078 < 0.1$.

Table 8. Synthesis of all criteria in benefit- composite weight.

Criteria/Options	Value Added	Safety	Efficiency	Social Benefits	Overall Priority
Anaerobic Digestion	0.237	0.042	0.038	0.154	0.471
Incineration	0.121	0.021	0.014	0.154	0.309
Compost	0.032	0.068	0.026	0.043	0.170
Landfill	0.020	0.008	0.004	0.018	0.050

4.2. Benefit Analysis

The particular aim of benefit analysis is to evaluate which waste treatment options would be the most beneficial to treat the amount of FBW generated. As well as the possibilities of increasing the efficiency rate, social benefits, and better resource recovery. The options on the left are objectively paired with the options on top in terms of value added, safety, efficiency, and social benefits in Tables 4–7, respectively.

Overall consistency of the hierarchy:

$$\text{ḈÎ́} = \frac{\sum_i \text{Wi CIi}}{\sum_i \text{Wi RIi}} = \frac{0.1445}{1.8000} = 0.080 < 0.1$$

The options on the left are objectively paired with the options on top in terms of value added, safety, efficiency, and social benefits in Tables 4–7 respectively. Each matrix priority was obtained from the comparisons matrix and presented in Table 8 and the standings of the choices are compared against the four criteria concerned. The entire matrix shown in Table 8. The result shown in Table 9 reports the idealized and normalized priorities. The idealized priority is obtained by dividing each priority by the largest value. So as to make the largest priority ideal alternative and while the others receive their proportionate value (same procedure is applied in the cost analysis). Subsequently, the result implies that anaerobic digestion has the highest benefit with 0.47 of its normalized priority, while incineration is about 65% of the benefit of anaerobic digestion, and so on.

Table 9. Normalized and idealized priorities.

Criteria/Options	Normalized Priorities	Idealized Priorities
Anaerobic Digestion	0.4714	1.0000
Incineration	0.3088	0.6551
Compost	0.1695	0.3596
Landfill	0.0502	0.1065

4.3. Cost Analysis

The specific objective of the cost analysis is to examine which waste treatment alternatives would be the least costly to treat the amount of FBW generated, along with the outcomes of reduction in air pollution, maintenance, and operating costs, renewable energy generation, ecological impact, and disamenity. The options on the left are paired with the options on top in terms of the cost of energy, operation, and maintenance, environmental constraints, and disruption/disturbance/disamenity in Tables 10–14 respectively.

Table 10. Pairwise comparison matrix of Criteria for cost.

Criteria	Energy	O&M	En Constraints	Disamenity	Priority
Energy	1	2.	2	2	0.3830
O&M	1/2	1	1/4	1/3	0.1089
En Constraints	1/2	4	1	1	0.2665
Disamenity	1/2	3	1	1	0.2415

Note: λmax = 4.2262, *CI* = 0.0754, *CR* = 0.067 < 0.1.

Table 11. Pairwise comparison matrix of the alternatives for energy.

Options	Anaerobic Digestion	Incineration	Compost	Landfill	Priority
Anaerobic Digestion	1	1/7	1/2	1/3	0.0663
Incineration	7	1	7	7	0.6813
Compost	2	1/7	1	1	0.1166
Landfill	3	1/7	1	1	0.1358

Note: λmax = 4.2102, *CI* = 0.0701, *CR*= 0.078 < 0.1.

Table 12. Pairwise comparison matrix of the alternatives for operation and maintenance.

Options	Anaerobic Digestion	Incineration	Compost	Landfill	Priority
Anaerobic Digestion	1	1/3	2	1/3	0.1348
Incineration	3	1	5	3	0.4955
Compost	1/2	1/5	1	1/5	0.0737
Landfill	3	1/3	5	1	0.2959

Note: λmax = 4.2360, *CI* = 0.0787, *CR* = 0.087 < 0.1.

Table 13. Pairwise comparison matrix of the alternatives for environmental constraints.

Options	Anaerobic Digestion	Incineration	Compost	Landfill	Priority
Anaerobic Digestion	1	1/5	2	1/9	0.0723
Incineration	5	1	8	1/9	0.3284
Compost	1/2	1/8	1	1/9	0.0461
Landfill	9	2	9	1	0.5532

Note: λmax = 4.0871, *CI*= 0.0290, *CR* = 0.032 < 0.1.

Table 14. Pairwise comparison matrix of the alternatives for disamenity.

Options	Anaerobic Digestion	Incineration	Compost	Landfill	Priority
Anaerobic Digestion	1	1/2	3	1/5	0.1287
Incineration	2	1	5	1/3	0.2333
Compost	1/3	1/5	1	1/9	0.0514
Landfill	5	3	9	1	0.5866

Note: λmax = 4.0590, *CI* = 0.0197, *CR* = 0.022 < 0.1.

Overall consistency of the cost hierarchy:

$$\acute{\c{C}}\acute{\hat{I}} = \frac{\sum_i \text{Wi CIi}}{\sum_i \text{Wi RIi}} = \frac{0.1233}{1.8000} = 0.068 < 0.1$$

Each matrix priority was obtained from the comparison matrix and presented in Table 14. The classifications of the alternatives were compared against the four criteria concerned. All matrixes are in synthesis in Table 15. The result in Table 16 shows the idealized and normalized score. Subsequently, the result implies that compost cost the least with 0.077 of its normalized priority, while anaerobic digestion costs about 9% less than compost, and so on.

Table 15. Synthesis for all criteria in cost - composite weight.

Criteria/Options	Energy	Operation	En Constraints	Disamenity	Overall Priority
Anaerobic Digestion	0.025	0.015	0.019	0.031	0.090
Incineration	0.261	0.054	0.088	0.056	0.459
Compost	0.045	0.008	0.012	0.012	0.077
Landfill	0.052	0.032	0.147	0.142	0.373

Table 16. Normalized and idealized priorities.

Criteria/Options	Normalized Priorities	Idealized Priorities
Anaerobic Digestion	0.0904	0.1971
Incineration	0.4588	1.0000
Compost	0.0774	0.1686
Landfill	0.3734	0.8137

4.4. Benefit Cost Analysis

From Table 8, one can conclude that the least cost alternative is composting, given that it scored the least, in addition, the alterative with the highest benefit priority is anaerobic digestion in the case of benefit analysis (Table 15). There is comparability in this instance, as the benefit and cost analysis lead toward different rankings [45]. Consequently, it is proper to carry out the benefit–cost ratio analysis to determine the final ranking based on the most suitable option in accordance with the outcomes of the benefit and cost examination. Therefore, judging from the result in Table 17, the benefit–cost ratio implies that anaerobic digestion remains a suitable alternative.

Table 17. Benefit cost analysis.

Criteria/Options	Cost	Benefit	Benefit/Cost
Anaerobic Digestion	0.0904	0.4714	5.2132
Incineration	0.4588	0.3088	0.6731
Compost	0.0774	0.1695	2.1907
Landfill	0.3734	0.0502	0.1345

4.5. Sensitivity Test

Sensitivity examination constitutes an integral part and standard procedure in MCDA to determine the soundness of the binding decision made and in what manner these diverse priority preferences influenced the judgments [28,39,52]. Thus, it explains the possibility of various informed decisions made by the decision-makers pertaining to the criteria adopted and how they exert influence on the judgment outcomes.

The examination was performed by modifying the priority weights of each criterion one at a time in a separate analysis of both benefit and cost and by compiling the account of the variations in the rank outcomes. The possible scenarios used for benefit and cost analyses are illustrated below:

(a) The first scenario illustrated how three out of four criteria are assigned with zero (0) priority weights while the remaining criterion was allocated with one in a composition of four potential chances. The benefit scenario is given in Figure 4a, while that of the cost is in Figure 5a, which ranked anaerobic digestion as optimal performing alternative in two of the criteria (value added and efficiency), and composting ranked top in safety criterion. Whereas both anaerobic digestion and composting maintained the same performance, in the case of cost analysis, incineration and land fill scored as the most cost effective alternatives in terms of energy, operation, and disamenity criteria, while composting and anaerobic digestion were the least cost efficient alternatives.

(b) The priority weights of 0.5 were assigned to two out of four criteria and zero (0) to the other in the second scenario (together with benefit and cost analysis) in a combination of six potential chances (similar results). Only one out of six possibilities are shown in Figures 4b and 5b, and the outcome is comparable to the outcome in the first scenario.

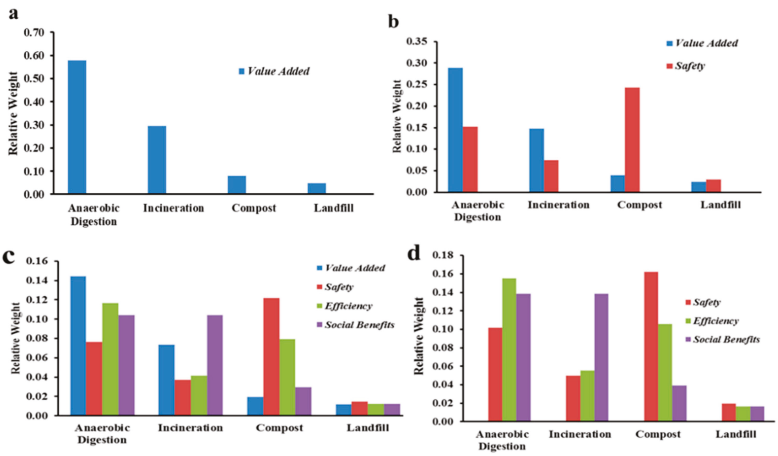

Figure 4. Sensitivity analysis: (**a**) only one criterion is assigned to the priority weight of one; (**b**) two criteria are allocated with 0.5; (**c**) all criteria have the same priority weight of 0.25; (**d**) three criteria are assigned to 0.33.

(c) The third scenario is the combination of only one possibility with all four criteria having equal priority weights of 0.25 each, for benefit and cost analysis (Figures 4c and 5c). The investigation presents an increasingly evident outcome similarly to the first scenario. Subsequently, the performance of anaerobic digestion and composting outweighs other alternatives in all the criteria both in the benefit and cost analysis. Consequently, it is proper to correctly deduce that anaerobic digestion is the utmost choice for proper FBW handling accompanied by compost as well as incineration, whereas landfill remains the worst [2].

(d) In the last scenario, three out of four of the criteria were assigned to the priority weight of 0.33 each, and zero (0) to the fourth criterion in a combination of four potential chances. Only one of the four possibilities (for benefit and cost analysis) is presented in Figures 4d and 5d, and the result shows a similar outcome to that of the third scenario.

The sensitiveness across all four scenarios shows similar outcomes, which can be inferred from Figures 4 and 5. Anaerobic digestion is seen to outperform other alternatives as to the most suitable choice for FBWM, followed by composting, which also had a more satisfactory performance in some of the criteria, and incineration. The last to be considered is landfill.

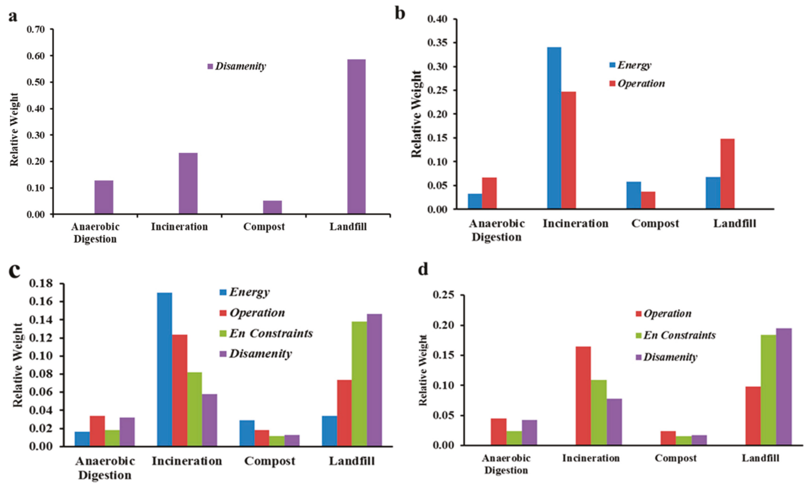

Figure 5. Sensitivity analysis: (**a**) only one criterion is assigned to the priority weight of one; (**b**) two criteria are allocated with 0.5; (**c**) all criteria have the same priority weight of 0.25; (**d**) three criteria are assigned to 0.33.

5. Discussion

In this study, benefit–cost analysis based on AHP model was the MCDA approach used to examine and assess the FBW treatment alternatives. The standard AHP model integrates a significant amount of pairwise comparisons amidst criteria, sub-criteria, and between choices within a dependable set of scaled weights, which facilitates choosing the appropriate decision. The model hierarchy in this study was separated into two parts of the analysis (benefit and cost) with each set of judgments, having one goal, four criteria, and four alternatives structured within three stages. The criteria comprised the main concerns involved in waste management, for instance, environmental, socio-cultural, technical, and economic aspects, leading to the development of the AHP based benefit–cost model. This model was utilized to assess and estimate the performance of each option and the result turned out to be in favor of anaerobic digestion. The analysis was done on a comparison scale, which meant the cost analysis against the benefit analysis.

However, the result shows that incineration and landfill hold respectively the highest cost priority weights of 0.4588 and 0.3734. Anaerobic digestion and compost hold a share lower priority value of 0.0904 and 0.0774. In the cost analysis, the cost of energy had the most significant relative weight of 0.3830among all the cost criteria. The environmental constraints and disamenity follow with their relative weight of 0.2665 and 0.2415, respectively, while operation and maintenance possess the most reduced relative weight of 0.1089.

Benefit analysis illustrates that anaerobic digestion is the most beneficial, with the relative weight of 0.4714. Incineration and compost are next with their resulting priority weights of 0.3088 and 0.1695. Value added had the highest priority weight of 0.4101 in the goal category and followed social benefits with the priority weight of 0.3685. While the system's efficiency and safety had theirs to be 0.824 and 0.1390. After the priority value of benefit and cost are separately analyzed, the adjusted priority weight of the benefit analysis was then divided by that of the cost analysis to produce the result. As such, the total standardized benefit–cost ratio was obtained for respective alternatives.

As a result, anaerobic digestion became the most uppermost benefit–cost ratio, with a priority weight of 5.2132. Compost had the next most relative weight of 2.1907. The worst options with the lowest benefit to cost ratios were incineration and landfill, respectively holding weights of 0.6731 and 0.1345. The sensitivity analysis performed on both benefit and cost resulted in using four different scenarios to see if there would be any change in the performance of the final result among all alternatives. The result showed a similar case as the synthesis result (final result), making anaerobic digestion the most suitable treatment alternative. Thus, it is demonstrated that the judgment of the treatment alternatives based on the criteria used for benefit and cost analyses was a robust one. The findings are comparable to the analysis carried out by Babalola [2] in a similar study.

However, incineration alone cannot achieve such sufficiency of using MSW as renewable resources. Similarly, there are numerous ecological benefits of treating FBW in anaerobic digestion. Same observation was made by Abba et al. [51] and Hanan et al. [52] in their application of the MCDA approach in selecting waste treatment alternatives based on their environmental impacts. In addition to these benefits is a decrease in the cost of treatment, an increase in combustion efficiency, as well as the value of recyclable materials and the reduction of the number of wet FBW substances. For this reason, it would be of a significant benefit if FBW were properly treated or disposed of in a more dependable treatment facility other than incineration [7,11,17,54,55].

Usually, stakeholder participatory or panel of experts are included in MCDA as part of the decision-making group that allocates weights and scores. It is extremely important to spell out that the weights used in this study were not based on monetary value, rather on the subjective judgments of the author founded on the standard of the Food Recycling Act in Japan and related literature. The subjective approach of this study is relevant to the application of AHP since only specific issues were being addressed. Therefore, the proposed framework does not require a large number of opinion experts in order to analyze the result. On the other hand, a higher degree of inconsistency is generally related to a large number of experts, as judgments made based on a diverse set of criteria would produce diverse results. Consequently, this study could be acknowledged as an adaptable framework that can be improved upon to fit in more criteria and options. In addition, it could provide an opportunity for more panels of experts or stakeholders to be involved in the decision-making process.

The AHP benefit–cost analysis demonstrated in this research signifies the operational effectiveness and practicality of its application in meaningfully addressing waste management concerns. Furthermore, it presents a significant understanding of the waste management objectives of Oita City, Japan.

6. Conclusions

The practical application of MCDA has emerged in the decision-making process as one essential instrument towards evaluating performance, choice of options, benefit–cost analysis, site selection, and making comparisons across plants, policies, private sectors, or time periods. AHP for evaluating performance, selection of options, benefit–cost analysis and site selection have become indispensable policy tools for decision makers. As the AHP benefit–cost analysis becomes more commonly applied in a variety of situations, MCDA approaches follow some key guidelines to make them fair and meaningful.

This study showed clearly a comparative assessment of the current FBW treatment option in Oita City, in line with the Food Waste Recycling Act. The investigation is in accordance with MSW practices (waste collection and disposal), the amount of generated waste, reuse, recycling, and reduction. Thus, the proposed solution could be seen as an enhancement upon the current practice and existing system of FBW management.

The outcomes implied the best and the most suitable alternatives aimed at handling the FBW was anaerobic digestion and followed by composting. Incineration became the third most suitable alternative in terms of the overall result, while landfill was assumed mostly as the worst-case because of the significant costs and low benefits.

The conceptual model illustrated in this study has the possibility to be employed as a systematic strategic decision supporting instrument. Capable of providing decision-makers with significant and dependable information on the assessment procedure of selecting the most appropriate disposal technology for FBW in accordance with economic, social, cultural, technical, and ecological concerns.

Subsequent research would be to apply the proposed framework in a factual situation using a committee of specialists and non-experts as well as monetized criteria where necessary (in cost analysis). Correspondingly, the committee of experts are allowed to explore different necessary conditions, parameters, and options of waste treatment from the ones analyzed in this paper.

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