land

MDPI

Article

A Sensitivity Index to Perform the Territorial Sustainability in Uncertain Decision-Making Conditions

Francesco Sica , Francesco Tajani *, Maria Rosaria Guarini and Rossana Ranieri

Department of Architecture and Design, Sapienza University of Rome, 00196 Rome, Italy
* Correspondence: francesco.tajani@uniroma1.it

Abstract: The issue of sustainability is central to development strategies. Although this alignment is acknowledged and shared world-wide, territorial development in a sustainable light must also take the ongoing COVID-19 pandemic into consideration, specifically by evaluating the effects of COVID-19 on the global health, social order, and economic-environmental system. The research suggests a sensitivity index to gauge the degree of territorial sustainability taking the COVID-19 pandemic's impacts into account. A study set of countries, as identified by the Organization for Economic Co-operation and Development (OECD), is used to test the developed index. The index evaluates a country's performance in terms of economic, social, and environmental sustainability while also considering the relative risk of COVID-19. The proposed index measures territorial sustainability from a variety of angles by enabling comparisons between the circumstances before and after current shocks in the socioeconomic and environmental performance frames by pandemic emergency. The index was created using an integrated assessment method that was based on the *Choquet* Integral (CI) mathematical framework and Multi-Attributive Ideal-Real Comparative Analysis (MAIRCA). The study establishes a unique and up-scaling methodology for constructing the sensitivity index, significantly advancing the suggestions for sustainable accounting under uncertain circumstances at the territorial scale. Adopting indices that quantify territorial sustainability under uncertainty may help guide policy decisions from an investment programming viewpoint, particularly when it comes to allocating financial resources to the economic sectors most impacted by shock events such as the COVID-19 pandemic.

Keywords: sustainable development; COVID-19; sensitivity index; integrated framework; *Choquet* Integral; Multi-Attributive Ideal-Real Comparative Analysis; OECD countries

Citation: Sica, F.; Tajani, F.; Guarini, M.R.; Ranieri, R. A Sensitivity Index to Perform the Territorial Sustainability in Uncertain Decision-Making Conditions. *Land* **2023**, *12*, 432. https://doi.org/10.3390/land12020432

Academic Editors: Maria Rosa Trovato and Salvatore Giuffrida

Received: 11 January 2023
Revised: 2 February 2023
Accepted: 3 February 2023
Published: 7 February 2023

1. Introduction

By 2019, the COVID-19 pandemic had begun to damage nations' development and growth dynamics world-wide, as well as the attainment of the 17 sustainable objectives established in the United Nations' Agenda 2030 [1,2]. According to the World Economic Forum's International Monetary Fund (IMF) estimate for 2020, the global economic-social and environmental assets will suffer the worst crisis since the "Great Depression" of 1929 [3].

Since the emergency broadened to a world-wide scale (2020–2021), the pandemic had significant effects on people's psychophysical health and sociality [4,5], national economic-productive performance [6], ecosystems condition [7], and climate change [8]. Inhibitions for halting the pandemic's spread had an impact on social contacts [9], which also had an effect on the country's manufacturing industry. Similar to the IMF report (2020), the global economy's growth outlook for 2020 shrank by 3%, as opposed to a forecast for 3.3% economic growth. Global gross domestic product (GDP) decreased by 1.8% in the first quarter of 2020 compared to the same period in 2019 [3]. Instead, the pandemic revealed important functional connections between the state of the biophysical ecosystems. Particularly during the lockdown periods, there was a rise in biodiversity, a supply of ecological services, and an improvement in air quality [10]. Air pollution and greenhouse gas emissions significantly reduced as a result of decreased human activity. According to Le Quéré et al. (2020), daily CO_2 emissions worldwide decreased 17% from the average level in 2019 [11].

The tourism industry, use of renewable energy sources, and educational system were all affected to an equal extent (World Economic Outlook, 2020). Even if the usage of renewable energy sources has risen, the World Travel and Tourism Council (WTTC) and the International Energy Agency (IEA) said that millions of jobs were at risk and that energy output had drastically decreased, respectively [12,13]. As a tactical move by industrialized nations to control the spread of the pandemic at the local level, the breakdown of the educational process in schools and higher education institutions reinforced the socio-economic disparities among students and their households significantly [14,15].

The highlighted impacts occur from exposure to a risk, such as a disturbance or stressor, which affects the important economic, social, and environmental elements that define the territory as a multidimensionally complex and fragile frame [6]. The United Nations (UN) asserted in its World Economic Situation and Prospects report for 2022 that efforts to stop the pandemic from spreading globally should serve as a roadmap for each nation to develop more resilient, egalitarian, and inclusive economies that are driven by sustainability objectives, encouraging investments to revive global trade, and lowering vulnerability to unexpected events [16].

This study suggests a sensitivity index that may be used to assess a territory's long-term performance as well as its relative trends before and after an emergency outbreak. The creation of the index is intended within an integrated framework that takes into account sustainability and the risk associated with the COVID-19 pandemic. The framework is organized in accordance with the Multi-Attributive Ideal-Real Comparative Analysis (MAIRCA) methodology. The latter was linked with the logical-mathematical ideas of Choquet's Integral (CI) for the aim of creating indices [17].

By utilizing the potential of each practical approach, the suggested evaluation model (MAIRCA-CI) integrates the MAIRCA phases with those of CI. In order to handle and resolve multi-criteria analysis instances where there is uncertainty, MAIRCA is based on a linear computational algorithm. It is primarily adaptable with other instruments, and it has a straightforward mathematical structure, which enables analysis that bridges the gap between ideal and empirical assessments [18]. As opposed to aggregative strategies based on geometric and arithmetic means, the CI enables the construction of indices by including the dependencies between assessment criteria for each alternative, establishing a mutual function between components, and adjusting the weighting parameter.

The remaining sections of the work are as follows: Section 2 highlights sustainable accounting in the context of vulnerability as discussed in the reference literature; Section 3 discusses the materials underlying the integrated process for index construction, specifically the description of the MAIRCA (3.1) and Choquet (3.2) approaches; Section 4 illustrates the logical-operational characteristics of the evaluation models used as a starting point for the definition of the integrated evaluation model (MAIRCA-CI); Section 5 includes the case-study; Section 6 details the findings and Section 7 presents the study's conclusion.

2. Reviewing the Relevant Studies

In several ways, the vulnerability discussion broadens public awareness [19,20]. In the international scientific literature, attempts to assess the sustainability of a territory can also be examined in relation to its relationship with unforeseen interactions [21–24]. Multiple studies looked at the sudden shifts in territorial systems brought on by temperature trends, variations in the frequency and intensity of rain, and increasing susceptibility to natural disasters [25–30]. A growing agreement identifies that understanding of the effects and responses by the affected system must go beyond disruptions and stressors, and places the majority of the blame for vulnerability on the dynamics of the human–environment system under uncertain conditions [31]. Vulnerability must be taken into account with respect to the system as well as the numerous linkages that might influence its condition [32].

Robust vulnerability analyses are required, and the relationship between scientific issues and the needs of decision-making is improving [32]. The literature supports the application of vulnerability analysis when it: (i) refers to the coupled human–environment system and relative conditions; (ii) identifies some components affecting the vulnerability of the system; (iii) measures the degree of vulnerability of a specific location; (iv) makes it simpler to identify critical points that suggest decision makers' actions; and (v) suggests the applicability of both quantitative and qualitative methodological approaches to manage information [19,20].

Regarding (v), the Risk-Hazard (RH) and Pressure-And-Release (PAR) models seem to be the most effective ways to demonstrate vulnerability [32]. RH seeks to understand how a risk affects an entity based on its sensitivity to the risk event and its exposure to it. The risk in the PAR model is intended to be a function of the perturbation, stressor, and vulnerability of the exposed unit. The assessment of the situations that might lead to hazard events and the requirement to comprehend vulnerability are the main points [33].

The sensitivity to stressors and perturbations differs between the two models. The political economy, especially social structures and institutions, are not addressed by the RH in terms of modifying exposure causes and effects, and the PAR does not address the human–environment system vulnerability from an integrated viewpoint [33].

The implementation of assessment techniques and tools based on multi-criteria logic, taking into account many and diverse variables within the same decision-making environment, is recommended by the literature to overcome the conceptual limitations of RH-PAR. The Analytic Hierarchy Process, Goal Programming, and the Multi-Attributive Ideal-Real Comparative Analysis for solving ranking cases between alternatives are a few examples of appropriate evaluation methods and tools to support the sustainability implementation in planning/design practices that were reviewed by Morano et al. in 2021 [34]. The creation of composite indicators for gauging socioeconomic well-being and the relative variation following unexpected occurrences have also been covered in the reference literature [35–43]. Long et al. (2020) depicted the sustainable performance of an islands-set in China referring to ecological wellbeing performance by the integration of the Three-Dimensional Ecological Footprint and Urban-Scale Human Development Index [35]. Shah et al. (2019) used the Energy Security and Environmental Sustainability Index, which combines energy and environmental indicators, to monitor energy security and environmental sustainability of South Asian countries [36]. Hansuebsai et al. (2020) introduced an environmental performance index to evaluate the activities of a printing house based on three impacts: carbon footprint, volatile organic compound emissions, and waste [37]. Richter and Behnisch (2019) combined geostatistical methods (landscape structure metrics, spatial multi-criteria assessment, weighting approaches) and a multitude of data related to environmental concerns. Based on the multi-criteria assessment, an index of landscape functions was calculated [38]. Tokimatsu et al. (2018) showed how the sustainability indicator Genuine Savings can be endogenized within a general equilibrium model and used as a criterion for judging the impacts of such policies in terms of future well-being [39]. Lind (2019) referred to the Human Development Index, published annually since 1990 by the United Nations Development Programme, to reflect 'development' as evident in the actual progression of life expectancy, education, and income in the world [40]. Kalimeris et al. (2020) explored the relevance of three welfare indicators—the Human Development Index, the Index of Sustainable Economic Welfare, and the Genuine Progress Indicator—as a basis for evaluating the dependency of welfare and its major engine, the economy, on natural resources [41]. Pais et al. (2019) assessed sustainable development for 28 Organization for Economic Co-operation and Development countries by computing a comparable Genuine progress indicator [42]. Vukoszavlyev (2019) studied the connection of innovation in 126 countries by different well-being indicators and whether there are differences among geographical regions with respect to the Global Innovation Index [43].

These primary implementations focus on three main goals: (i) monitoring of the environment with energy usage [35,36,43,44]; (ii) study of the long-term consequences of territorial policies aimed (for example) at reducing the risk of natural catastrophes [37–39,45–50]; and (iii) tracking the economic growth at the country level in relation to the well-being status and ecosystem condition [39–43]. In the latter, the creation of sensitivity indices was put to the test in an effort to enhance knowledge of vulnerability and future forecasts of it in territorial analysis techniques. Many people in both fields concentrated on calculating the geometric and mathematical means; others, however, relied on the application of operational strategies widely used in game and decision theory, for example, the Choquet Integral.

3. Materials

The suggested methodological framework aims to express the performance related to territorial sustainability and, in particular, it is capable of describing the adaptability of sustainable territorial development assets to changes in the economic, social, and environmental conditions, taking into account before/after the COVID-19 pandemic conditions. In order to promote robust and dynamic decision-making systems for territorial development from a sustainable viewpoint, the suggested protocol of multi-criteria matrix aims to present a sensitivity evaluation index.

As previously stated, the suggested index is realized in accordance with the logical-operative flow of the MAIRCA combined with the CI. The following lists the stages for the MAIRCA (3.1) and CI (3.2) techniques.

3.1. The MAIRCA Method for Gap Analysis Implementation

Professor Dragan Pamučar of the Belgrade Defence University defined the MAIRCA approach [51]. It is based on the logical-operational notion of a “ideal solution” that is connected to the evaluation issue to be addressed [52], and it is often utilized and tested in a variety of decision settings, as well as in combination with various multi-criteria and geographic analytic approaches. In particular, Gigović et al. (2016) used geographic information systems and the MAIRCA technique to solve a scenario of choosing between two locations without a clear functional purpose for the development of new infrastructure [53]. In order to decrease the number of road fatalities, Pamučar et al. (2018) used an integrated evaluation procedure that used the Full Consistency Method and the MAIRCA when allocating level crossings [18]. By defining priorities for selection using the MAIRCA technique coupled with fuzzy principles, Pamučar et al. (2019) analyzed six potential territorial regions to identify the landing site of vehicles in combat operations [54]. In 2018, Badi and Ballem combined MAIRCA with the Best-Worst Method (BWM) [55]; Chatterjee et al. coupled MAIRCA with the Analytic Network Process [56]; in 2019, Ulutaş combined MAIRCA with Step-Wise Weight Assessment Ratio Analysis. To determine the ideal staffing level for an organization’s IT department [57], Aycin (2020) created the inter-criteria correlation (CRITIC) and MAIRCA methods [58], Arsić et al. (2019) conducted a multi-criteria evaluation with the adoption of BWM and MAIRCA methods [59]. In the research by Chatterjee et al. (2020), the MAIRCA method was used to evaluate environmentally friendly lightweight materials in terms of their performance in the automotive manufacturing sector [60].

Given the numerous implementations of the MAIRCA approach throughout the final decade of the twenty-first century, it is efficient in measuring the gaps for several choices in multiple contexts. The general evaluative scenario may have the optimal solution represented by that with the smallest total gap value [51,53].

The MAICA is very adaptable to various decision-scenarios due to its implementation capability in conjunction with other tools. In general, the MAIRCA is composed of operational matrix phases that are sequential and may be used as a guide for structuring decision-making analysis in terms of problem identification, impact assessment, values elicitation, information synthesis, applying the results to enhance decision-making, and challenging thinking. In order to gather appropriate data and support the single stage effectively so that it respects the nature of the decision scenario of reference, the integration of these stages with additional technologies is frequently necessary.

The six sequential steps that make up the MAIRCA approach stand out are as follows [18].

3.1.1. Step 1: Criteria Identification and Creating Initial Decision Matrix

Having identified which criteria C_i (with $i = 1, \ldots, n$) to include in the evaluation of alternatives A_j (with j = 1, . . . , m), the values of the assessment criteria for each alternative are organized in a matrix (X) of the type:

$$\mathrm{X} = \begin{bmatrix} A_1 \\ \ldots \\ A_m \end{bmatrix} \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix} \begin{bmatrix} C_1 & \ldots & C_n \end{bmatrix} \quad (1)$$

3.1.2. Step 2: Determining the Alternative Priorities

Once the matrix (X) has been constructed, the principle of ordering alternatives is established. The Pamučar axiom of the MAIRCA method consists in the absence of a priority law to be applied in the process of selecting and ordering between alternatives [18]. Each alternative is of equal importance to the others.

The priority of the j-th alternative $\left(Pr_{A_j}\right)$ is calculated according to the following algebraic equalities (2):

$$Pr_{A_j} = \frac{1}{m};\ \sum_{j=1}^{m} Pr_{A_j} = 1 \quad (2)$$

3.1.3. Step 3: Construction of the Theoretical Rating Matrix

The elements of the Theoretical Rating Matrix $\left(T_p\right)$ are obtained considering the priority factors of j-th alternative with respect to the i-th criterion. Specifically, the elements $t_{p_{ij}}$ of T_p are obtained by multiplying the priorities Pr_{A_j} by the corresponding weight factor $\left(w_j\right)$. The matrix T_p [m × m] takes on the following algebraic configuration (3):

$$\mathrm{T_p} = \begin{bmatrix} \mathrm{Pr_{A_1} \cdot w_1} & \cdots & \mathrm{Pr_{A_1} \cdot w_m} \\ \vdots & \ddots & \vdots \\ \mathrm{Pr_{A_m} \cdot w_1} & \cdots & \mathrm{Pr_{A_m} \cdot w_m} \end{bmatrix} \quad (3)$$

3.1.4. Step 4: Defining the Real Rating Matrix

The matrix T_r is derived from the combination of the matrix T_p and that of the initial decision (X). Equations (4) and (5) evaluate the T_r elements in accordance with the greatest and lowest values of the j-th alternative to the i-th criterion, respectively. The generic component $t_{r_{ij}}$ of T_r is considered the weighted average value of the results from the (4) and (5).

$$\mathrm{t_{r_{ij}}} = \mathrm{t_{p_{ij}}} \cdot \frac{\left(\mathrm{x_{ij}} - \mathrm{x_{ij}^-}\right)}{\left(\mathrm{x_{ij}^+} - \mathrm{x_{ij}^-}\right)} \quad (4)$$

$$\mathrm{t_{r_{ij}}} = \mathrm{t_{p_{ij}}} \cdot \frac{\left(\mathrm{x_{ij}} - \mathrm{x_{ij}^+}\right)}{\left(\mathrm{x_{ij}^-} - \mathrm{x_{ij}^+}\right)} \quad (5)$$

In (4) and (5), x_{ij}^+ is the highest value of the numerical series relating to the criterion (C_i) by which A_j is assessed $[x_{ij}^+ = max(x_1, x_2, \cdots, x_m)]$; meanwhile x_{ij}^- identifies the corresponding lowest value $[x_{ij}^- = min(x_1, x_2, \cdots, x_m)]$.

3.1.5. Step 5: Computation of Total Gap Matrix

The difference between the matrix X e T_r gives the Total Gap Matrix (G) which assumes an algebraic configuration of the type:

$$G = T_p - T_r = \begin{bmatrix} g_{11} & \cdots & g_{1n} \\ \vdots & \ddots & \vdots \\ g_{1m} & \cdots & g_{mn} \end{bmatrix}$$

The value of g_{ij} in G matrix is commensurate with the difference between the T_p e T_r, i.e., the matrices representing respectively the reference value of the i-th criterion with respect to the j-th alternative ($t_{p_{ij}}$), and the corresponding real value as a result of evaluations carried out on the basis of pre-established reference targets ($t_{r_{ij}}$).

3.1.6. Step 6: Final Value of the Alternatives

In view of the (G) matrix, it is possible to derive the final score (Q_j) for the alternative (A_j) on the basis of the relative differences in values in T_p e T_r for each criterion C_i (con i = 1, ... , n). The parameter (Q_j) can be calculated by means of the geometric series such as Equation (6) below:

$$Q_j = \sum_{i=1}^{n} g_{ij} \tag{6}$$

From the Q_j values it is possible to identify the alternative (A_j) whose performance characteristics differ, significantly or not, from the target values of each criterion (C_i). When the differential between $t_{p_{ij}}$ e $t_{r_{ij}}$ of the alternative A_j tends to zero, the A_j is performing in consideration of the (C_i).

In order to overcome Jean-Pierre Brans' problems with prioritizing techniques amongst alternatives, the MAIRCA approach was created [61], but the lack of thresholds for preference and/or indifference in the aggregate of the gaps of each choice is one of its limitations in terms of compensation. Due to the interaction between the components and the mutual numerical differential, the Choquet Integral (CI) stands out as an aggregation operator from weighted average operators to close this gap. The CI and the associated stages for the development of composite evaluation indices enabling the prioritizing of alternatives based on the relative trade-offs of each criterion are discussed in the next sub-section. The CI's description is relevant to Section 4 in regard to the MAIRCA-CI evaluation framework.

3.2. The Choquet Integral

The most popular weighted average operators are generalized in Choquet integrals. Choquet's measures appear to be practical modeling tools for the mutual interdependencies in interacting decision systems, as in the Decision Theory. Murofushi and Soneda investigate reciprocity between the components in more detail [62,63]. As a gauge of the relative weight of the various assessment criteria, they employed the Shapley value. Grabisch and Roubens noticed the idea of using indices to quantify the significance and degree of interaction between subsets, and they subsequently applied it to the multi-criteria analysis theory [64,65].

The implementation of CI developed in the twenty-first century. In complex decision-making systems, Meyer and Ponthière used the CI to express individual preferences [66–69]. In order to create indices based on interactions between performance indicators and pre-established reference objectives, Carraro et al. (2013) employed the CI [70]. Merad et al. (2013), Bertin et al. (2018), Bottero et al. (2015) and (2018), Branke et al. (2016), and Campagnolo et al. (2018) all conducted similar exercises [71–76]. Grabisch et al. (2008) used CI together with participative methodologies to determine how much each evaluation criterion should matter in light of stakeholder assessments [77].

In light of the literature references, a baseline operation is discernible. The following is an explanation.

Given a set N = {l, 2, . . . , n}—i.e., a finite set of *n* interacting elements, the components of N may represent decision agents, or even criteria characterizing a multi-criteria decision problem. A discrete Choquet measure on the set N is a function $\mu : P(N) \rightarrow [0, 1]$ that satisfies the following two conditions, the boundary (1) and monotony condition (2), respectively:

1. μ (0) = 0; μ(D) = 1;
2. for any S, T⊆D, S⊆T⊆D → $\mu(S) \leq \mu(T) \leq \mu(D)$.

The quantity μ(S), with S ⊆ N, represents the value of the coalition S without the other elements in N\S. The μ(T) refers to the Choquet measure in a subset T of the analysis-domain D, whereas the μ(D) concerns the Choquet measure on the analysis-domain border.

If $\mu(i)$ represents the weight of *i*, in 1992 Murofushi proposed the use of an importance index within the framework of the multi-criteria decision theory. The same was introduced in 1953 by Shapley in Game Theory, defining the Shapley power index [62,78].

Shapley's power index (or Shapley's value) for each element $i \in N$ ($\theta_\mu^{(i)}$) is measured by means of the following Equation (7):

$$\begin{aligned} \theta_\mu^{(i)} &= \sum_{T \subseteq N \setminus i} \frac{(n-1-t)!t!}{n!} \left[\mu\,(T \cup i) - \mu\,(T)\right] = \\ &= \frac{1}{n} \sum_{t=0}^{n-1} \binom{n-1}{t}^{-1} \sum_{T \subseteq N \setminus i} \left[\mu\,(T \cup i) - \mu\,(T)\right] \end{aligned} \quad (7)$$

The (7) can take on a compact algebraic connotation as that follows (8):

$$\theta_\mu^{(i)} = \frac{1}{|N|!} \sum_{\pi \in \pi_N} \mu(CI(\pi, i) \cup \{i\}) - \mu(CI(\pi, i)) \quad (8)$$

The Shapley value of an element *i* expresses the contribution of *i* to all possible coalitions (π) with other components. Shapley values, for any element *i* in N, are always positive, assuming values between [0÷1].

Based on the Shapley value of each element $\mu\left(x_{(i)}\right)$ it is possible to define the corresponding Choquet integral $C_\mu(x)$ as follows (9):

$$C_\mu(x) = \sum_{i=1}^{n} x_{(i)} \left[\theta\left(x_{(i)}\right) - \theta\left(x_{(i+1)}\right)\right] = x_{(i)} \left[\theta\left(x_{(i)}\right) - \theta\left(x_{(i+1)}\right)\right] = \theta\left(x_{(i)}\right) \left[x_{(i)} - x_{(i-1)}\right] \quad (9)$$

4. The MAIRCA-CI Model

For the purpose of creating assessment indices with which to quantify the variability of the reference decision scenario from a sustainable perspective, the suggested model incorporates the MAIRCA properties together with those that distinguish the CI. The Shapley value and Choquet measure will be used, respectively, for the assignment of weights to each analytical element and for the formulation of a sensitivity index, as per the methodological framework of MAIRCA, which has been agreed to be kept. The methodologically integrated approach (MAIRCA-CI) put forward facilitates the assessment of the territorial circumstances in regard to any potential discrepancy of their sustainable frame brought on by unforeseen occurrences such as the COVID-19 pandemic. Public and private decision-makers can greatly benefit from the monitoring of sustainability levels even in the face of abrupt changes in socioeconomic and environmental systems when restructuring strategic development assets to be used at the territorial scale and, as a result, when redistributing available financial resources among development projects.

Following are the phases that define the proposed MAIRCA-CI assessment model's flow:

Step 1: Criteria identification and creating initial decision matrix (X);

Step 2: Determining the Priorities of Alternatives (Pr_{A_j}) and weights factors by means of Shapley measure. Construction of the Theoretical and Real Rating Matrix (T_p, T_r);

Step 3: Computation of Total Gap Matrix (G) and Index construction with Choquet integral.

The theoretical and practical premises supporting the suggested paradigm of analysis include:

- linear ordering of the assessment criteria so that they may be compared in a predetermined order i (where $i = 1, \ldots, n$) in accordance with the set of criteria's consistency (of index i);
- evaluation of each criterion's weighting elements using the Shapley measure, which considers the i-th criterion's varying degree of coupling with the other criteria of order $(i - 1)$. The preferences of possible stakeholders in the decision-making process are not taken into account while applying the Shapley formula;
- decision-makers' preferences are not used to determine how each alternative is weighted; rather, an egalitarian significance factor is used to do so.
- The following subsections detail each stage.

4.1. Criteria Identification and Creating Initial Decision Matrix (X)

The sustainable assessment of each potential alternative is conducted using the proper evaluation criteria and performance indicators to quantify and qualitatively analyze each criterion. The criteria and relative indicators should be chosen in accordance with the following factors: (i) the particulars of the evaluation case to be solved; (ii) the sustainability dimensions to be examined for each alternative; and (iii) the likelihood of measuring each criterion via a particular indicator in relation to the availability of geo-referenced and NOR data, information systems, and the analysis scale of reference. The criteria C_i (with $i = 1, \ldots, n$) screened according to the principles of inclusion/exclusion illustrated above found elements in the initial decision matrix X where the indicators values for each criterion (matrix columns) can be organized in correspondence to each alternative A_j (with $j = 1, \ldots, m$). The initial decision matrix takes on a configuration of the type in (1).

In order to be able to compare each j-th alternative to the other, it is necessary to normalize the values of X, so as to obtain the $\overline{X}$ in which to include the results by the normalization practice. The normalization process must respect both the theoretical framework and the properties of available data.

There are several ways to put it into practice [79,80]. The "Min-Max" normalization intended for the suggested technique of analysis is recommended, whereby the normalized indicators (I_n) have an identical range [0, 1] by subtracting the minimum value and dividing by the range of indicator values i as follows:

$$I_n = \frac{x_i - \min_i x}{\max_i x - \min_i x} \tag{10}$$

In (10), x_i is the value of the indicator referred to the i-th criterion, $\min_i x$ the minimum of the numerical series relative to the i-th indicator; $\max_i x$ refers to the maximum of the series itself.

4.2. Determining the Priorities of Alternatives and Weights Factors by Means of Shapley Measure. Construction of the Theoretical and Real Rating Matrix (T_p,T_r)

Starting by the X-matrix we proceed to the construction of the Theoretical Rating Matrix (T_p) of which each element $t_{p_{ij}}$ is obtained by multiplying the priority factor of the single alternative by the weight of the i-th criterion. The i-weights are estimated using the Shapley measure (see Equation (7)). By integrating (7) into (2), T_p is reshaped as follows:

$$T_p = \begin{bmatrix} Pr_{A_1} \cdot \theta_{\mu}^{(1)} & \cdots & Pr_{A_1} \cdot \theta_{\mu}^{(m)} \\ \vdots & \ddots & \vdots \\ Pr_{A_m} \cdot \theta_{\mu}^{(1)} & \cdots & Pr_{A_m} \cdot \theta_{\mu}^{(m)} \end{bmatrix} \quad (11)$$

namely,

$$T_p = \begin{bmatrix} Pr_{A_1} \\ \cdots \\ Pr_{A_m} \end{bmatrix} \cdot \begin{bmatrix} \theta_{\mu}^{(1)} & \ldots & \theta_{\mu}^{(m)} \end{bmatrix} \quad (12)$$

The $\theta_{\mu}^{(i)}$ are calculated on the basis of the amount of the criteria. Equation (8) in Section 4 is used for their assessment. On the basis of the values of T_p it is possible, then, to realize the Real Rating Matrix T_r as described within Step 4 of 4.1 in Section 4.

4.3. Computation of Total Gap Matrix (G) and Index Construction with Choquet Measurement

The last step of the proposed analysis model is the construction of the Total Gap Matrix (G) based on the difference between the average of the values extracted from (4) and (5) with the values of the initial evaluation matrix constructed within Step 1. As function of the differentials related to the matrix G, valuation indices are determined for the j-th alternative. By using the Choquet measurement and the algebraic formulation (9) in Section 4, the evaluation index j is created.

5. Case-Study

The aim is to assess and analyze the degree of sustainable development of OECD nations in light of the socio-economic and environmental consequences of the COVID-19 pandemic crisis. Each nation must pay close attention to the execution of investments targeted at attaining the sustainable development goals of the Agenda 2030, according to international governmental and other legal measures for the post-COVID-19 recovery period. By gathering information pertaining to the second quarter of 2020, the influence of COVID-19 on the performance of sustainable development within the triple profile of economic-social and environmental for 35 OECD nations was examined (1. Australia, 2. Austria, 3. Belgium, 4. Canada, 5. Chile, 6. Colombia, 7. Czech Republic, 8. Denmark, 9. Estonia, 10. Finland, 11. France, 12. Germany, 13. Greece, 14. Hungary, 15. Iceland, 16. Ireland, 17. Israel, 18. Italy, 19. Japan, 20. Korea, 21. Latvia, 22. Lithuania, 23. Luxembourg, 24. Mexico, 25. Netherlands, 26. New Zealand, 27. Norway, 28. Poland, 29. Portugal, 30. Slovak Republic, 31. Slovenia, 32. Spain, 33. Sweden, 34. Switzerland, 35. Turkey).

The three processes at the core of the MAIRCA-CI integrated assessment model (see Section 4) are used to advance the case study's development in terms of:

Step 1: Defining sustainability criteria and creating the initial study-set evaluation matrix;

Step 2: Weighting the evaluation sustainability criteria;

Step 3: Constructing the sensitivity index with *Choquet* measurement.

Each of the steps above is devolved into a subsection as follows.

5.1. Defining Sustainability Criteria and Creating the Initial Study-Set Evaluation Matrix

To ascertain the sustainable level for the countries under study, acceptable criteria and corresponding performance indicators must be identified while putting up the first decision matrix. The OECD, European Union, and United Nations sustainable development goals were used to generate the sustainable development indicators for OECD nations. The OECD database's Green Growth Indicators were specifically taken into account. The 35 OECD nations are included in the database [81].

The case study's indicators were chosen using clear sustainability benchmarks to highlight the essential elements of green growth: (1) environmental protection; (2) economic productivity; and (3) social well-being. For each significant aspect, indicators characteristic of the reference dimension are considered, such as production-based CO_2 emissions (C1), real GDP per capita (C2), and life expectancy at birth (C3). Through comparable units of measurement, such as tons for C1, dollars for C2, and years for C3, the indicators under consideration are related to measurable things. These metrics were chosen to monitor nations' advancements toward green growth in support of territorial decision-making frameworks. It makes sense to assume that, based on the particular evaluative scenario, further and more indications may also be used.

In addition to the sustainability indicators (C1, C2, C3), the Inform COVID-19 Risk Index (C4) is also taken into consideration as an additional performance indicator to identify countries at risk from health and humanitarian impacts of COVID-19 that could overwhelm current national response capacity, and therefore lead to a need for additional international assistance. The adoption of C4 for each nation supports giving early reaction measures for the key pandemic consequences priority. The following website has information about C4: https://drmkc.jrc.ec.europa.eu/inform-index/INFORM-COVID-19 (last accessed: 20 December 2022).

Table 1 provides the initial decision matrix with C1, C2, C3, and C4 values for each of the 35 countries analyzed. Table 2 contains the values numbers of Table 1 normalized by means of the algebraic expression (10) in Section 4 in order to standardize data to the same measurement scale.

Table 1. Initial decision matrix of alternatives assessed under the four criteria.

	Production-Based CO_2 Emissions [Tonnes]	Real GDP per Capita [USD]	Life Expectancy at Birth [Years]	Inform COVID-19 Risk Index [0–10]
Australia	375.98	46,225.27	83.64	2.10
Austria	57.27	48,737.82	81.77	3.00
Belgium	83.31	44,906.81	81.86	2.80
Canada	523.19	43,446.19	82.67	2.00
Chile	79.74	21,662.19	80.42	3.10
Colombia	70.35	12,524.04	77.53	4.30
Czech Republic	84.34	36,059.28	79.57	3.40
Denmark	25.57	52,109.98	81.11	2.10
Estonia	8.60	33,214.55	78.89	3.00
Finland	35.70	44,480.50	82.14	2.10
France	258.23	41,170.83	82.86	3.00
Germany	585.26	47,499.52	81.57	2.20
Greece	46.59	26,536.37	82.47	3.30
Hungary	43.63	30,473.28	77.04	3.40
Iceland	1.47	52,977.67	83.22	2.50
Ireland	31.63	88,490.38	82.51	3.00
Israel	57.97	39,534.71	83.19	2.70
Italy	280.37	35,211.43	83.71	3.20
Japan	1.024.07	40,416.16	84.79	2.30
Korea	570.74	41,654.84	83.20	4.80
Latvia	6.37	28,294.46	75.46	3.40
Lithuania	10.79	35,362.04	76.11	2.80
Luxembourg	7.48	104,591.30	82.47	0.00
Mexico	381.00	16,989.68	75.24	3.70
Netherlands	134.71	52,493.26	82.49	2.50
New Zealand	33.10	40,784.45	82.51	2.10
Norway	36.11	60,470.83	82.63	1.80
Poland	267.64	31,305.22	78.94	3.10
Portugal	37.33	30,997.88	82.29	2.80
Slovak Republic	26.50	31,640.41	77.72	3.30

Table 1. *Cont.*

	Production-Based CO_2 Emissions [Tonnes]	Real GDP per Capita [USD]	Life Expectancy at Birth [Years]	Inform COVID-19 Risk Index [0–10]
Slovenia	11.76	35,061.91	81.54	2.60
Spain	194.79	34,250.05	83.74	2.80
Sweden	32.14	50,412.39	83.03	2.20
Switzerland	34.12	66,240.84	83.97	1.90
Turkey	366.11	28,160.55	77.99	3.90

Table 2. Initial decision matrix, of which the values were normalized by means of formula (10) in Section 4.

	Production-Based CO_2 Emissions	Real GDP per Capita	Life Expectancy at Birth	Inform COVID-19 Risk Index
Australia	0.3662	0.3661	0.8796	0.4375
Austria	0.0546	0.3933	0.6838	0.6250
Belgium	0.0800	0.3517	0.6932	0.5833
Canada	0.5102	0.3359	0.7780	0.4167
Chile	0.0765	0.0993	0.5424	0.6458
Colombia	0.0674	0.0000	0.2398	0.8958
Czech Republic	0.0810	0.2556	0.4534	0.7083
Denmark	0.0236	0.4300	0.6147	0.4375
Estonia	0.0070	0.2247	0.3822	0.6250
Finland	0.0335	0.3471	0.7225	0.4375
France	0.2511	0.3112	0.7979	0.6250
Germany	0.5709	0.3799	0.6628	0.4583
Greece	0.0441	0.1522	0.7571	0.6875
Hungary	0.0412	0.1950	0.1885	0.7083
Iceland	0.0000	0.4394	0.8356	0.5208
Ireland	0.0295	0.8251	0.7613	0.6250
Israel	0.0553	0.2934	0.8325	0.5625
Italy	0.2727	0.2464	0.8869	0.6667
Japan	1.0000	0.3030	1.0000	0.4792
Korea	0.5567	0.3164	0.8335	1.0000
Latvia	0.0048	0.1713	0.0230	0.7083
Lithuania	0.0091	0.2481	0.0911	0.5833
Luxembourg	0.0059	1.0000	0.7571	0.0000
Mexico	0.3711	0.0485	0.0000	0.7708
Netherlands	0.1303	0.4341	0.7592	0.5208
New Zealand	0.0309	0.3070	0.7613	0.4375
Norway	0.0339	0.5208	0.7738	0.3750
Poland	0.2603	0.2040	0.3874	0.6458
Portugal	0.0351	0.2007	0.7382	0.5833
Slovak Republic	0.0245	0.2076	0.2597	0.6875
Slovenia	0.0101	0.2448	0.6597	0.5417
Spain	0.1890	0.2360	0.8901	0.5833
Sweden	0.0300	0.4115	0.8157	0.4583
Switzerland	0.0319	0.5835	0.9141	0.3958
Turkey	0.3566	0.1698	0.2880	0.8125

5.2. Weighting the Evaluation Sustainability Criteria

The Theoretical Rating Matrix (T_p) by estimating the priority factor (Pr_{A_j}) according to the number of reference alternatives (A_j) for the weight of each criterion. The estimation of the i-th weight (with i = 1, . . . , 4) is performed via Equation (8) of Section 3. Table 3 shows the theoretical rating matrix (T_p) related to the case study.

Table 3. The Theoretical Rating Matrix (T_p) where weight factors for each possible combination between the evaluation criteria were defined using the mathematical expression in Section 4.2.

T_p =		{**C1**}	{**C2**}			
	A_j	0.001429	0.000952	0.000952	0.000714	0.167

On the basis of the information included in the T_p, we proceed to create the Real Rating Matrix (T_r) via the mathematical formula described within Step 4 of 4.1 in Section 4. Table 4 presents the Tr specific of the case-study examined.

Table 4. The values of the Real Rating Matrix (T_r) for the case study. Each numerical element was defined by means of the formulas (4) and (5) in Section 3.1.

	C1	**C2**	**C3**	**C4**
Australia	0.001020	0.000811	0.000952	0.000031
	0.000409	0.000142	0.000000	0.000683
Austria	0.000135	−0.000653	−0.000661	−0.000311
	0.001293	0.000173	0.000291	0.000404
Belgium	0.000207	0.001169	0.000674	0.000248
	0.001221	0.000173	0.000278	0.000466
Canada	0.001429	0.000744	0.000800	0.000000
	0.000000	0.000208	0.000152	0.000714
Chile	0.000197	0.000220	0.000451	0.000342
	0.001231	0.000733	0.000502	0.000373
Colombia	0.000171	0.000000	0.000000	0.000714
	0.001257	0.000952	0.000952	0.000000
Czech Republic	0.000210	0.000566	0.000318	0.000435
	0.001381	0.000000	0.000635	0.000280
Denmark	0.000047	0.000952	0.000558	0.000031
	0.001381	0.000000	0.000395	0.000683
Estonia	0.000000	0.000498	0.000212	0.000311
	0.001429	0.000455	0.000740	0.000404
Finland	0.000075	0.082307	0.000136	−0.000009
	0.001353	−0.081355	0.000816	0.000723
France	0.000693	0.076181	0.000137	−0.000008
	0.000736	−0.075229	0.000815	0.000722
Germany	0.001601	0.087894	0.000135	−0.000009
	−0.000172	−0.086942	0.000817	0.000723
Greece	0.000105	0.049097	0.000137	−0.000007
	0.001323	−0.048144	0.000816	0.000722
Hungary	0.000097	0.056383	0.000127	−0.000007
	0.001331	−0.055430	0.000826	0.000722
Iceland	−0.000020	0.098033	0.000138	−0.000008
	0.001448	−0.097081	0.000814	0.000723
Ireland	0.000064	0.163759	0.000137	−0.000008
	0.001365	−0.162806	0.000816	0.000722
Israel	0.000137	0.073153	0.000138	−0.000008
	0.001292	−0.072201	0.000814	0.000722
Italy	0.000754	0.065152	0.000139	−0.000007
	0.000674	−0.064200	0.000813	0.000722
Japan	0.002819	0.074785	0.000141	−0.000009
	−0.001391	−0.073832	0.000811	0.000723
Korea	0.001561	0.077077	0.000138	−0.000005
	−0.000132	−0.076125	0.000814	0.000720
Latvia	−0.000006	0.052350	0.000124	−0.000007
	0.001435	−0.051398	0.000829	0.000722

Table 4. *Cont.*

	C1	C2	C3	C4
Lithuania	0.000006	0.065431	0.000125	−0.000008
	0.001422	−0.064478	0.000827	0.000722
Luxembourg	−0.000003	0.193558	0.000137	−0.000012
	0.001432	−0.192605	0.000816	0.000726
Mexico	0.001034	0.031428	0.000123	−0.000007
	0.000395	−0.030476	0.000829	0.000721
Netherlands	0.000350	0.097137	0.000137	−0.000008
	0.001078	−0.096184	0.000816	0.000723
New Zealand	0.000068	0.075466	0.000137	−0.000009
	0.001361	−0.074514	0.000816	0.000723
Norway	0.000076	0.111901	0.000137	−0.000009
	0.001352	−0.110949	0.000815	0.000724
Poland	0.000719	0.057923	0.000130	−0.000008
	0.000709	−0.056970	0.000822	0.000722
Portugal	0.000080	0.057354	0.000136	−0.000008
	0.001349	−0.056401	0.000816	0.000722
Slovak Republic	0.000050	0.058543	0.000128	−0.000007
	0.001379	−0.057591	0.000824	0.000722
Slovenia	0.000009	0.064875	0.000135	−0.000008
	0.001420	−0.063923	0.000817	0.000723
Spain	0.000517	0.063373	0.000139	−0.000008
	0.000912	−0.062420	0.000813	0.000722
Sweden	0.000065	0.093285	0.000138	−0.000009
	0.001363	−0.092333	0.000815	0.000723
Switzerland	0.000071	0.122580	0.000139	−0.000009
	0.001358	−0.121628	0.000813	0.000724
Turkey	0.000992	0.052103	0.000128	−0.000007
	0.000436	−0.051150	0.000824	0.000721

5.3. Constructing the Sensitivity Index with Choquet Measurement

The Total Gap Matrix (G) is shown in Table 5 as a prerequisite to the building of the assessment index of each country's sustainability level commensurate with the relevant degree of risk from COVID-19. The Choquet Integral is then used to define the sustainable evaluation index of the studied nations (see Section 3.2). The Choquet Integral adopts the following algebraic form in regard to the selected case study:

$$\begin{aligned} C_{\mu}(i) = \sum_{i=1}^{35}(\{C1\}) \quad & *C1 + (\{C2\}) * C2 + (\{C3\}) * C3 + (\{C4\}) * C4 + (\{C1, C2\}) + (\{C1\}) \\ & +(\{C2\}) \times \min(C1, C2) + [(\{C1, C3\}) + (\{C1\}) + (\{C3\})] \times \min(C1, C3) \\ & +[(\{C1, C4\}) + (\{C1\}) + (\{C4\})] \times \min(C1, C4) \\ & +[(\{C2, C3\}) + (\{C2\}) + (\{C3\})] \times \min(C2, C3) \\ & +[(\{C2, C4\}) + (\{C2\}) + (\{C4\})] \times \min(C2, C4) \\ & +[(\{C3, C4\}) - (\{C3\}) - (\{C4\})] \times \min(C3, C4) + [1 - (\{C1, C2\}) - (\{C1, C3\}) \\ & -(\{C1, C4\}) - (\{C2, C3\}) - (\{C2, C4\}) - (\{C3, C4\}) + (\{C1\}) + (\{C2\}) + (\{C3\}) \\ & +(\{C4\})] \times \min(C1, C2, C3, C4) \end{aligned} \quad (13)$$

Table 5. The Total Gap Matrix (G) specifically for the case-study. Their elements (g_{ij}) are deduced from the difference between the normalized values of Table 2 and the average of each couple of values in Table 4.

	C1	C2	C3	C4
Australia	0.713218	0.850867	0.999524	0.043121
Austria	0.144473	0.818277	0.707969	0.347780
Belgium	0.137533	0.230172	0.472907	0.477904
Canada	0.146464	0.594059	0.333130	0.608339
Chile	0.137533	0.230367	0.472907	0.477904
Colombia	0.119280	−0.000476	−0.000476	0.999643
Czech Republic	0.146383	0.594252	0.333130	0.608339
Denmark	0.032267	0.999524	0.585167	0.043121
Estonia	−0.000714	0.522197	0.222244	0.434425
Finland	0.051937	0.806792	0.754358	0.043121
France	0.484396	0.723185	0.871264	0.434425
Germany	1.119901	0.883057	0.659636	0.086599
Greece	0.073108	0.353496	0.808410	0.564860
Hungary	0.067354	0.452948	−0.080540	0.608339
Iceland	−0.014571	1.021443	0.930715	0.217034
Ireland	0.044036	1.918547	0.813449	0.434425
Israel	0.095230	0.681854	0.925186	0.303991
Italy	0.527404	0.572641	1.011237	0.521382
Japan	1.972652	0.704120	1.186907	0.130078
Korea	1.091695	0.735411	0.927541	1.217034
Latvia	−0.005047	0.397908	−0.339219	0.608339
Lithuania	0.003545	0.576446	−0.233241	0.347469
Luxembourg	−0.002888	2.325280	0.807658	−0.869922
Mexico	0.722975	0.112333	−0.375701	0.738773
Netherlands	0.244360	1.009206	0.811322	0.217034
New Zealand	0.046886	0.713424	0.813678	0.043121
Norway	0.052743	1.210731	0.834226	−0.087314
Poland	0.502666	0.473964	0.230718	0.477904
Portugal	0.055113	0.466201	0.778636	0.347469
Slovak Republic	0.034068	0.482432	0.031196	0.564860
Slovenia	0.361099	0.548355	1.015164	0.347469
Spain	0.045021	0.956640	0.898683	0.086599
Sweden	0.048873	1.356490	1.053216	−0.043835
Switzerland	0.694021	0.394525	0.075269	0.825730
Turkey	0.048873	1.356490	1.053216	−0.043835

The {C1}, {C2}, {C3}, {C4}, {C1, C2}, {C1, C3}, {C1, C4}, {C2, C3}, {C2, C4}, {C3, C4} are in Table 3.

6. Discussion

The significance of the interdependencies between pandemic risk and sustainable level at territorial scale can be considered in light of the results (see Tables 5 and 6) obtained by the application of the proposed evaluation model.

The COVID-19 pandemic's effects on each of the 35 nations' partial (Table 5) and overall (Table 6) sustainability performance may be tractable through the MAIRCA-CI model. Even in the presence of uncertainty and variability in the reference decision-making environment, analysis of the numerical values in Tables 5 and 6 enables observations about the performance of each country from the perspective of economic, social, and environmental sustainability.

Table 6. The Table 6 expresses the Choquet Integral index of the 35-countries study. The specific value is obtained by the formula (13).

	$C_{\mu}(i)$
Australia	1.0301
Austria	0.8259
Belgium	0.5993
Canada	0.7509
Chile	0.5999
Colombia	0.1280
Czech Republic	0.7508
Denmark	0.4008
Estonia	0.3896
Finland	0.4816
France	1.3527
Germany	1.0787
Greece	0.6714
Hungary	0.1758
Iceland	0.6151
Ireland	0.8870
Israel	0.7241
Italy	1.4570
Japan	1.3713
Korea	2.2938
Latvia	−0.2679
Lithuania	−0.1350
Luxembourg	−0.7043
Mexico	−0.0852
Netherlands	0.9129
New Zealand	0.4613
Norway	0.3644
Poland	0.9233
Portugal	0.5978
Slovak Republic	0.3178
Slovenia	1.0762
Spain	0.5829
Sweden	0.5264
Switzerland	0.7605
Turkey	0.5264

The Total Gap matrix of country values for each indicator is shown by Table 5. Each indicator's reading provides information on the change in performance, if any. Observe how a decrease in the danger of pandemic exposure is matched by a marked improvement in the nation's performance, first economically and then socially. Considering the real GDP per capita trade-off values in relation to those typical of COVID-19, for instance, in the countries of Luxembourg, Sweden, and Norway shows how exposure to dangerous occurrences may alter a region's level of productivity and innovation, thereby slowing down the nation's sustainable economic progress [43]. In addition, it is evident that high pandemic risk values correlate with decline in the community's social and physical well-being from the standpoint of social sustainability. Consider the situations of Colombia, Mexico, and Latvia as examples. This demonstrates how a territory's human development, as measured by social welfare within the community, may be influenced by exposure to the danger of population-destabilizing events, whether that exposure is high or low [40].

The performance of nations under each criterion in respect to their own degree of riskiness may also be analyzed using the suggested assessment model, but the MAIRCA-CI model enables a synthetic comparison of geographical realities. In fact, the synthetic index in Table 6 takes into consideration both the COVID-19 risk component and individual variations in sustainability performance. Note that it is a measure of the effect—whether favorable or unfavorable—on the potential for sustainable development in each country. It should go without saying that using a single numerical parameter makes it easier to carry out tasks targeted at resolving ranking situations in relation to the world-wide context of study. Comparisons across geographic realities can be restricted to the year of information retrieval or by calculating the index to a year earlier or before the zero-reference year; it is feasible to compare the loss or gain in sustainable performance by nation.

According to Table 6, Colombia, Hungary, Latvia, Lithuania, Mexico, and the Slovak Republic all saw variations in sustainability performance during the first quarter of 2020, with values for the indicators ranging from 20% to 85%.

The trend line of the index that summarizes each country's sustainability performance and that which refers to its unique risk factor via COVID are shown in Figure 1 as follows. The indicator values for the nations included in the study set are also shown.

The COVID-19 pandemic broke out in the second quarter of 2020, at which time the sustainability performances of the various nations were compared to those of the same quarter the year before. This is to emphasize the influence of the COVID-19 hazard on territorial performance, as in the case study examined, in comparison to a baseline setting free of pandemic risk. The suggested MAIRCA-CI assessment approach is used to reassess the sustainable assessment indices across the 35 research nations. The indices for 2020 and 2019 are suggested in Figure 2. For each country, the percentage difference between the indices is provided.

It is conceivable that some areas' economic, social, and environmental sustainability performance has significantly declined as a result of the information gathered. Some of the first nations to observe the pandemic's quick spread between 2019 and 2020 are France (−16.30%), Italy (−19.66%), and Korea (−27.58%). These circumstances should be explored in light of their insightful characteristics from an environmental, economic, and social point of view. However, depending on how risky they are in terms of COVID-19, as shown by their individual Inform COVID-19 Risk Index scores, there is a minor drop in their sustainability levels. Last but not least, there are examples of nations' own economic, social, and environmental sustainability improving, as in the situations of Luxembourg (+32.62%), Mexico (+14.09%), and Latvia (+12.72%), some of the last nations to be affected by the pandemic catastrophe at the start of the global emergency.

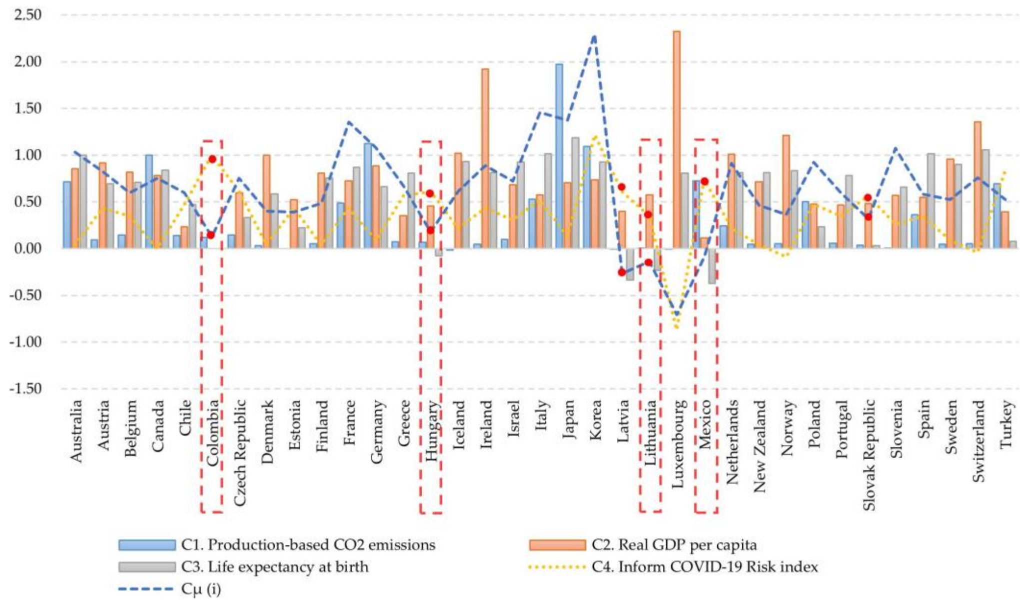

Figure 1. Evolution of the research nations' sustainability levels in respect to their own risk tolerance according to COVID-19. Examples of a strong relationship between territorial riskiness and sustainability are given.

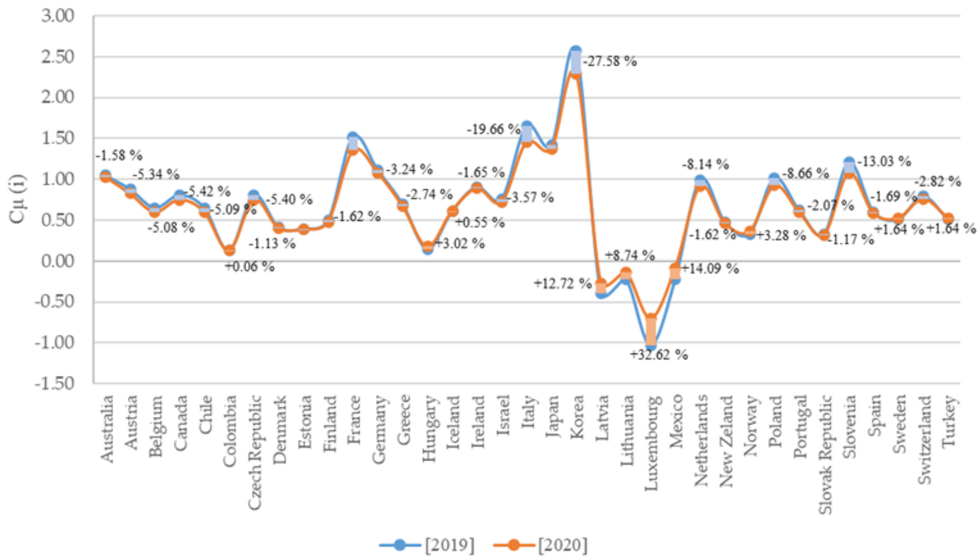

Figure 2. Alterations in the sustainability levels of the study nations, taking into account the corresponding evaluation indices between 2019 and 2020 using the suggested accounting method.

7. Conclusions

In light of the case study's findings, complex decision-making systems can benefit from simplification in their management and resolution due to the MAIRCA-CI model's multi-criteria nature, which enables it to simultaneously take into account various aspects and keys to reading the landscape within a single framework from a sustainability-sensitive perspective. The suggested sensitivity index is even framed as a tool capable of capturing recognized assessment criteria via the use of performance indicators accepted globally by organizations such as the OECD. The use of artificial risk indices of COVID-19, such as the one in the suggested case study, has also made it possible to qualify the suggested assessment model in a dynamic way, allowing for the adaptation and application of the algorithm in a variety of temporal scenarios, even during an epidemic emergency, in order to monitor the long-term viability of the study system. The construction of a synthetic assessment index with which to qualitatively convey the influence that the risk from COVID-19 had on the level of economic, social, and environmental sustainability of the region resulted from the integration of the MAIRCA model with the integral CI. Consequently, methods of monitoring and evaluation at a territorial level are made easier. In particular, policymakers may benefit from the monitoring and assessment phase of sustainability performance trends as they plan and allocate resources for spatial development projects. Understanding the nature of territorial sustainable development aids decision-makers in making sound financial resource allocations and adhering to a distribution criterion suitable for the economic, social, and environmental particularities of the target setting.

The choice of sustainability indicators to be used in the assessment phase, the use of indices that summarize the level of uncertainty related to the disasters in study, and the application of the technique at a scale other than territorial are all examples of research constraints. Regarding this final consideration, research focuses will include putting the proposed MAIRCA-CI model to the test at the city scale, taking a variety of indicators into consideration, and looking into the possibility of expressing the shocks through other measurement indices that are not necessarily qualitative but are more closely related to the dynamics of the relevant territorial/urban context.

Author Contributions: Conceptualization, F.S. and F.T.; methodology, F.S. and F.T.; validation, F.T. and M.R.G.; formal analysis, F.T.; investigation, F.S. and R.R.; resources, F.S.; data curation, F.S. and R.R.; writing—original draft preparation, F.S. and F.T.; writing—review and editing, F.T. and R.R.; visualization, F.S., F.T., M.R.G., and R.R.; supervision, F.T. and M.R.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding. The current study has been developed within the current research “Post-COVID future cities. Methods and Tools to Design and Assess, Healthy, Sustainable and Resilient Suburbs”, and “Resilience and sustainability of urban regeneration initiatives. Methods for assessing the effectiveness of investments on the built environment”, Sapienza University of Rome.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

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

References

1. Deloitte Annual Turkish M&A Review. 2019. Available online: https://www2.deloitte.com/tr/en.html (accessed on 23 December 2022).
2. ONU. Trasformare il Nostro Mondo: L’Agenda 2030 per lo Sviluppo Sostenibile. 2015. Available online: https://oneplanetschool.wwf.it/sites/default/files/2020-09/Agenda-2030-Onu-italia.pdf (accessed on 23 December 2022).
3. World Economic Outlook. The Great Lockdown. 2020. Available online: https://www.imf.org/en/Publications/WEO/Issues/2020/04/14/weo-april-2020 (accessed on 13 November 2022).
4. Cullen, W.; Gulati, G.; Kelly, B.D. Mental health in the COVID-19 pandemic. *QJM Int. J. Med.* **2020**, *113*, 311–312. [CrossRef] [PubMed]
5. Chakraborty, I.; Maity, P. COVID-19 outbreak: Migration, effects on society, global environment and prevention. *Sci. Total Environ.* **2020**, *728*, 138882. [CrossRef] [PubMed]
6. Michie, J. The covid-19 crisis–and the future of the economy and economics. *Int. Rev. Appl. Econ.* **2020**, *34*, 301–330. [CrossRef]
7. Zambrano-Monserrate, M.A.; Ruano, M.A.; Sanchez-Alcalde, L. Indirect effects of COVID-19 on the environment. *Sci. Total Environ.* **2020**, *728*, 138813. [CrossRef]
8. Fuentes, R.; Galeotti, M.; Lanza, A.; Manzano, B. COVID-19 and climate change: A tale of two global problems. *Sustainability* **2020**, *12*, 8560. [CrossRef]
9. Vokó, Z.; Pitter, J.G. The effect of social distance measures on COVID-19 epidemics in Europe: An interrupted time series analysis. *GeroScience* **2020**, *42*, 1075–1082. [CrossRef]
10. Lawler, O.K.; Allan, H.L.; Baxter, P.W.; Castagnino, R.; Tor, M.C.; Dann, L.E.; Hungerford, J.; Karmacharya, D.; Lloyd, T.J.; López-Jara, M.J.; et al. The COVID-19 pandemic is intricately linked to biodiversity loss and ecosystem health. *Lancet Planet. Health* **2021**, *5*, e840–e850. [CrossRef]
11. Le Quéré, C.; Jackson, R.B.; Jones, M.W.; Smith, A.J.; Abernethy, S.; Andrew, R.M.; De-Gol, A.J.; Willis, D.R.; Shan, Y.; Canadell, J.G.; et al. Temporary reduction in daily global CO_2 emissions during the COVID-19 forced confinement. *Nat. Clim. Chang.* **2020**, *10*, 647–653. [CrossRef]
12. World Travel Tourism Council. 2020. Available online: https://wttc.org/ (accessed on 10 January 2023).
13. IEA. COVID-19, Exploring the Impacts of the COVID-19 Pandemic on Global Energy Markets, Energy Resilience, and Climate Change. 2020. Available online: https://www.iea.org/topics/covid-19 (accessed on 7 December 2022).
14. Akat, M.; Karataş, K. Psychological Effects of COVID-19 Pandemic on Society and Its Reflections on Education. *Electron. Turk. Stud.* **2020**, *15*, 1–13. [CrossRef]
15. Gonzalez, T.; De La Rubia, M.A.; Hincz, K.P.; Comas-Lopez, M.; Subirats, L.; Fort, S.; Sacha, G.M. Influence of COVID-19 confinement on students’ performance in higher education. *PLoS ONE* **2020**, *15*, e0239490. [CrossRef]
16. UN. The World Economic Situation and Prospects. 2022. Available online: https://www.un.org/development/desa/dpad/wpcontent/uploads/sites/45/publication/WESP2022_web.pdf (accessed on 21 December 2022).
17. Liern, V.; Pérez-Gladish, B. Multiple criteria ranking method based on functional proximity index: Un-weighted TOPSIS. *Ann. Oper. Res.* **2020**, *311*, 1099–1121. [CrossRef]
18. Pamučar, D.S.; Pejcic Tarle, S.; Parezanovic, T. New hybrid multi-criteria decision-making DEMATEL MAIRCA model: Sustainable selection of a location for the development of multimodal logistics centre. *Econ. Res. Ekon. Istraživanja* **2018**, *31*, 1641–1665. [CrossRef]
19. Cash, D.W.; Clark, W.C.; Alcock, F.; Dickson, N.M.; Eckley, N.; Guston, D.H.; Jäger, J.; Mitchell, R.B. Knowledge systems for sustainable development. *Proc. Natl. Acad. Sci. USA* **2003**, *100*, 8086–8091. [CrossRef]
20. Giuffrida, S.; Trovato, M.R.; Circo, C.; Ventura, V.; Giuffrè, M.; Macca, V. Seismic Vulnerability and Old Towns. A Cost-Based Programming Model. *Geosciences* **2019**, *9*, 427. [CrossRef]
21. Baker, S.M. Vulnerability and resilience in natural disasters: A marketing and public policy perspective. *J. Public Policy Mark.* **2009**, *28*, 114–123. [CrossRef]

22. de Oliveira Mendes, J.M. Social vulnerability indexes as planning tools: Beyond the preparedness paradigm. *J. Risk Res.* **2009**, *12*, 43–58. [CrossRef]
23. Taylor, M. Climate change, relational vulnerability and human security: Rethinking sustainable adaptation in agrarian environments. *Clim. Dev.* **2013**, *5*, 318–327. [CrossRef]
24. Lee, Y.J. Social vulnerability indicators as a sustainable planning tool. *Environ. Impact Assess. Rev.* **2014**, *44*, 31–42. [CrossRef]
25. Dell, M.; Jones, B.F.; Olken, B.A. Temperature shocks and economic growth: Evidence from the last half century. *Am. Econ. J. Macroecon.* **2012**, *4*, 66–95. [CrossRef]
26. Cavallo, E.; Galiani, S.; Noy, I.; Pantano, J. Catastrophic natural disasters and economic growth. *Rev. Econ. Stat.* **2013**, *95*, 1549–1561. [CrossRef]
27. Dell, M.; Jones, B.F.; Olken, B.A. What do we learn from the weather? The new climate-economy literature. *J. Econ. Lit.* **2014**, *52*, 740–798. [CrossRef]
28. Hsiang, S.M.; Jina, A.S. The causal effect of environmental catastrophe on long-run economic growth. Evidence from 6.700 cyclones. *Natl. Bur. Econ. Res.* **2014**, 20352.
29. Burke, M.; Hsiang, S.M.; Miguel, E. Global non-linear effect of temperature on economic production. *Nature* **2015**, *527*, 235–239. [CrossRef] [PubMed]
30. Cattaneo, C.; Peri, G. The migration response to increasing temperatures. *J. Dev. Econ.* **2016**, *122*, 127–146. [CrossRef]
31. Mileti, D. *Disasters by Design: A Reassessment of Natural Hazards in the United States*; Joseph Henry Press: Washington, DC, USA, 1999.
32. Cutter, S.L. *American Hazardscapes: The Regionalization of Hazards and Disasters*; Joseph Henry Press: Washington, DC, USA, 2002.
33. Turner, B.L.; Kasperson, R.E.; Matson, P.A.; McCarthy, J.J.; Corell, R.W.; Christensen, L.; Eckley, N.; Kasperson, J.X.; Luers, A.; Martello, M.L.; et al. A framework for vulnerability analysis in sustainability science. *Proc. Natl. Acad. Sci. USA* **2003**, *100*, 8074–8079. [CrossRef]
34. Morano, P.; Tajani, F.; Guarini, M.R.; Sica, F. A systematic review of the existing literature for the evaluation of sustainable urban projects. *Sustainability* **2021**, *13*, 4782. [CrossRef]
35. Long, X.; Yu, H.; Sun, M.; Wang, X.C.; Klemeš, J.J.; Xie, W.; Wang, C.; Li, W.; Wang, Y. Sustainability evaluation based on the Three-dimensional Ecological Footprint and Human Development Index: A case study on the four island regions in China. *J. Environ. Manag.* **2020**, *265*, 110509. [CrossRef]
36. Shah, S.A.A.; Zhou, P.; Walasai, G.D.; Mohsin, M. Energy security and environmental sustainability index of South Asian countries: A composite index approach. *Ecol. Indic.* **2019**, *106*, 105507. [CrossRef]
37. Hansuebsai, A.; Kaosod, A.; Kanchanasing, T. A new environmental performance index based on the carbon footprint, VOC emissions, and waste in a printing house. *Eng. Rep.* **2020**, *2*, e12165. [CrossRef]
38. Richter, B.; Behnisch, M. Integrated evaluation framework for environmental planning in the context of compact green cities. *Ecol. Indic.* **2019**, *96*, 38–53. [CrossRef]
39. Tokimatsu, K.; Dupuy, L.; Hanley, N. Using genuine savings for climate policy evaluation with an integrated assessment model. *Environ. Resour. Econ.* **2019**, *72*, 281–307. [CrossRef]
40. Lind, N. A development of the human development index. *Soc. Indic. Res.* **2019**, *146*, 409–423. [CrossRef]
41. Kalimeris, P.; Bithas, K.; Richardson, C.; Nijkamp, P. Hidden linkages between resources and economy: A "Beyond-GDP" approach using alternative welfare indicators. *Ecol. Econ.* **2020**, *169*, 106508. [CrossRef]
42. Pais, D.F.; Afonso, T.L.; Fuinhas, A. Are economic growth and sustainable development converging? Evidence from the comparable Genuine Progress Indicator for Organisation for Economic Co-operation and Development Countries. *Int. J. Energy Econ. Policy* **2019**, *9*, 202. [CrossRef]
43. Vukoszavlyev, S. The connenction between global innovation index and economic well-being indexes. *Appl. Stud. Agribus. Commer.* **2019**, *13*, 87–92. [CrossRef]
44. Trovato, M.R.; Giuffrida, S. The Protection of Territory from the Perspective of the Intergenerational Equity. In *Integrated Evaluation for the Management of Contemporary Cities*; SIEV 2016. Green Energy and Technology; Mondini, G., Fattinnanzi, E., Oppio, A., Bottero, M., Stanghellini, S., Eds.; Springer: Cham, Switzerland, 2018; pp. 469–485. [CrossRef]
45. Giuffrida, S.; Trovato, M.R. A Semiotic Approach to the Landscape Accounting and Assessment. An Application to the Urban-Coastal Areas. In Proceedings of the 8th International Conference on Information and Communication Technologies in Agriculture, Food and Environment, HAICTA 2017, Chania, Greece, 21–24 September 2017; Volume 2030, pp. 696–708.
46. Salata, F.; Golasi, I.; Peña-García, A.; Ciancio, V.; Yousefi, Z. A first approach to a new index on indoor lighting comfort based on corneal illuminance. *J. Daylighting* **2019**, *6*, 124–130. [CrossRef]
47. Manganelli, B.; Morano, P.; Tajani, F.; Salvo, F. Affordability assessment of energy-efficient building construction in Italy. *Sustainability* **2019**, *11*, 249. [CrossRef]
48. Ribeiro, P.J.G.; Gonçalves, L.A.P.J. Urban resilience: A conceptual framework. *Sustain. Cities Soc.* **2019**, *50*, 101625. [CrossRef]
49. Morano, P.; Locurcio, M.; Tajani, F.; Guarini, M.R. Urban Redevelopment: A Multi-criteria Valuation Model Optimized through the Fuzzy Logic. In *Computational Science and Its Applications—ICCSA 2014: 14th International Conference, Guimarães, Portugal, 30 June–3 July 2014*; Lecture Notes in Computer Science; Springer: Cham, Switzerland, 2014; Volume 8581. [CrossRef]

50. Morano, P.; Guarini, M.R.; Sica, F.; Anelli, D. Ecosystem Services and Land Take. A Composite Indicator for the Assessment of Sustainable Urban Projects. In *Computational Science and Its Applications—ICCSA 2021: 21st International Conference, Cagliari, Italy, 13–16 September 2021*; Lecture Notes in Computer Science; Springer: Cham, Switzerland, 2021; Volume 12954. [CrossRef]
51. Pamučar, D.; Mihajlović, M.; Obradović, R.; Atanasković, P. Novel approach to group multi-criteria decision making based on interval rough numbers: Hybrid DEMA^{TEL}-ANP-MAIRCA model. *Expert Syst. Appl.* **2017**, *88*, 58–80. [CrossRef]
52. Gul, M.; Ak, M.F. Assessment of occupational risks from human health and environmental perspectives: A new integrated approach and its application using fuzzy BWM and fuzzy MAIRCA. *Stoch. Environ. Res. Risk Assess.* **2020**, *34*, 1231–1262. [CrossRef]
53. Gigović, L.; Pamučar, D.; Bajić, Z.; Milićević, M. The combination of expert judgment and GIS-MAIRCA analysis for the selection of sites for ammunition depots. *Sustainability* **2016**, *8*, 372. [CrossRef]
54. Pamučar, D.S.; Ćirović, G.; Božanić, D. Application of interval valued fuzzyrough numbers in multi-criteria decision making: The IVFRN-MAIRCA model. Yugoslav. *J. Oper. Res.* **2019**, *29*, 221–247. [CrossRef]
55. Badi, I.; Ballem, M. Supplier selection using the rough BWM-MAIRCA model: A case study in pharmaceutical supplying in Libya. *Decis. Mak. Appl. Manag. Eng.* **2018**, *1*, 16–33. [CrossRef]
56. Chatterjee, K.; Pamučar, D.; Zavadskas, E.K. Evaluating the performance of suppliers based on using the R'AMATEL-MAIRCA method for green supply chain implementation in electronics industry. *J. Clean. Prod.* **2018**, *184*, 101–129. [CrossRef]
57. Ulutaş, A. The Selection of Caterıng Fırm with Swara and Maırca Methods. *Bus. Manag. Stud. Int. J.* **2019**, *7*, 1467–1479. [CrossRef]
58. Ayçin, E. Using CRITIC and MAIRCA Methods in Personnel Selection Process. *Bus. J.* **2020**, *1*, 1–12.
59. Arsić, S.N.; Pamučar, D.; Suknovic, M.; Janošević, M. Menu evaluation based on rough MAIRCA and BW methods. *Serb. J. Manag.* **2019**, *14*, 27–48. [CrossRef]
60. Chatterjee, P.; Mandal, N.; Dhar, S.; Chatterjee, S.; Chakraborty, S. A novel decision-making approach for light weight environment friendly material selection. *Mater. Today Proc.* **2019**, *22*, 1460–1469. [CrossRef]
61. Brans, J.P.; Vincke, P. Note—A preference ranking organisation method. *Manag. Sci.* **1985**, *31*, 647–656. [CrossRef]
62. Murofushi, T. A technique for reading fuzzy measures (I): The Shapley value with respect t o a fuzzy measure. In Proceedings of the 2nd Fuzzy Workshop, Nagaoka, Japan, 1992.
63. Murofushi, T.; Soneda, S. Techniques for reading fuzzy measures (III): Interaction index. In Proceedings of the 9th Fuzzy System Symposium, Sapporo, Japan, 1993; pp. 693–696.
64. Grabisch, M. k-order additive discrete fuzzy measures and their representation. *Fuzzy Sets Syst.* **1997**, *92*, 167–189. [CrossRef]
65. Roubens, M. Interaction between criteria and definition of weights in MCDA problems. In Proceedings of the 44th Meeting of the European Working Group "Multicriteria A id for Decisions", Brussels, Belgium, 1996. Available online: https://www.euro-online.org/web/ewg/1/ewg-mcda-euro-working-group-on-multiple-criteria-decision-aiding (accessed on 27 December 2021).
66. Meyer, P.; Ponthière, G. Eliciting preferences on multi-attribute societies with a Choquet Integral. *Comput. Econ.* **2011**, *37*, 133–168. [CrossRef]
67. Angilella, S.; Bottero, M.; Corrente, S.; Ferretti, V.G.; Lami, S.; Lami, I. Non additive robust ordinal regression for urban and territorial planning: An application for siting an urban waste landfill. *Ann. Oper. Res.* **2016**, *245*, 427–456. [CrossRef]
68. Oppio, A.; Bottero, M.; Arcidiacono, A. Assessing urban quality: A proposal for a MCDA evaluation framework. *Ann. Oper. Res.* **2022**, *312*, 1427–1444. [CrossRef]
69. Gálvez Ruiz, D.; Diaz Cuevas, P.; Braçe, O.; Garrido-Cumbrera, M. Developing an index to measure sub-municipal level urban sprawl. *Soc. Indic. Res.* **2018**, *140*, 929–952. [CrossRef]
70. Carraro, C.; Campagnolo, L.; Eboli, F.; Lanzi, E.; Parrado, R.; Portale, E. Quantifying sustainability: A new approach and world ranking. *FEEM Work. Pap.* **2012**. [CrossRef]
71. Merad, M.; Dechy, N.; Serir, L.; Grabisch, M.; Marcel, F. Using a multi-criteria decision aid methodology to implement sustainable development principles within an organization. *Eur. J. Oper. Res.* **2013**, *224*, 603–613. [CrossRef]
72. Bertin, G.; Carrino, L.; Giove, S. The Italian regional well-being in a multi-expert non-additive perspective. *Soc. Indic. Res.* **2018**, *135*, 15–51. [CrossRef]
73. Bottero, M.; Ferretti, V.; Figueira, J.R.; Greco, S.; Roy, B. Dealing with a multiple criteria environmental problem with interaction effects between criteria through an extension of the ELECTRE III method. *Eur. J. Oper. Res.* **2015**, *245*, 837–850. [CrossRef]
74. Bottero, M.; Ferretti, V.; Figueira, J.R.; Greco, S.; Roy, B. On the Choquet multiple criteria preference aggregation model: Theoretical and practical insights. *Eur. J. Oper. Res.* **2018**, *271*, 120–140. [CrossRef]
75. Branke, J.; Corrente, S.; Greco, S.; Słowiński, R.; Zielniewicz, P. Using Choquet integral as preference model in interactive evolutionary multiobjective optimization. *Eur. J. Oper. Res.* **2016**, *250*, 884–901. [CrossRef]
76. Campagnolo, L.; Carraro, C.; Eboli, F.; Farnia, L.; Parrado, R.; Pierfederici, R. The Ex-Ante evaluation of achieving sustainable development goals. *Soc. Indic. Res.* **2018**, *136*, 73–116. [CrossRef]
77. Grabisch, M.; Kojadinovic, I.; Meyer, P. A review of methods for capacity identification in Choquet integral based multi-attribute utility theory applications of the Kappalab R package. *Eur. J. Oper. Res.* **2008**, *186*, 766–785. [CrossRef]
78. Shapley, L.S. A value for n-person games. In *Contributions to the Theory of Games*; Annals of Mathematics Studies; Kuhn, H.W., Tucker, A.W., Eds.; Princeton University Press: Princeton, NJ, USA, 1953; Volume II, pp. 307–317.
79. Freudenberg, M. *Composite Indicators of Country Performance: A Critical Assessment*; OECD: Paris, France, 2003.

80. Jacobs, R.; Smith, P.; Goddard, M. *Measuring Performance: An Examination of Composite Performance Indicators*; Technical Paper Series 29; Centre for Health Economics: York, UK, 2004.
81. OECD. "Green Growth Indicators", OECD Environment Statistics (Database). Available online: https://doi.org/10.1787/data-00665-en (accessed on 2 February 2023).