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Multi-Criteria Analysis and Sustainable Accounting. Defining Indices of Sustainability under Choquet's Integral

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Abstract: The assessment of sustainability—in its three meanings: economic, social, and environmental ones—needs to be supported by specific econometric and statistical methodologies in order to be properly considered in policymaking processes. In the current literature the use of specific indices, capable of summarizing the three fields of sustainability, is a proven operational practice to express judgments on the convenience and the feasibility of investment in cities. It is necessary to specify that most sustainability indices are ordinarily calculated as arithmetic and geometric means of sub-dimensions. However, these two approaches do not allow investigation of the potential interactions between the various dimensions considered and, specifically, the geometric mean fails to smooth out unbalanced links. The research carried out here is aimed at implementing the use of the Choquet integral, as a non-additive and flexible aggregation model, to calculate evaluation indices able to consider the relationships between the different sustainable dimensions to be used in urban transformation projects. The methodology was tested on a case study, concerning an analysis—under economic, social, and environmental points of view—of different European countries. The evaluation frame based on the Choquet integral is referred to a ranking case aimed to establish the most sustainable country under the economic, environmental, and social point of view. The results obtained from the index processing show that the geometric mean scores and arithmetic ones are rather homogeneous, while the variations obtained among the three dimensions are moderately large. In the synoptic picture obtained with Choquet's integral, countries with balanced results across dimensions are in higher positions. Therefore, the Choquet integral allows positive interactions to be taken into account across sustainable dimensions, and it is able to detect unbalanced achievements.

Keywords: sustainable investments; multi-criteria analysis; evaluation indices; Choquet integral

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1. Introduction

In the economic assessment of investments in the urban context, in reference to the concept of well-being, the measurement of income as a single control parameter cannot be considered sufficient [1,2]. In a multidimensional perspective linked to the three aspects of sustainability—namely of economic, social, and environmental types—it is necessary to consider further multiple aspects other than income [3,4].

In a world-wide context, the political agenda at country level considers the improvements in the well-being field when assessing the social development in relation to the environmental protection and the economic growth of the territory. Following the Istanbul Declaration [5] and the Global Project on the Measurement of the Progress of Societies by the Organization for Economic Co-operation and Development (OECD) [6] both established in 2008, new methodological and political initiatives on how to go

"Beyond Gross Domestic Product (GDP)" to measure the well-being and the sustainable development have been applied. Hence, there is a growing sense against the benchmark related on how the progress of a society should not be measured only on final goods and services produced, but it should be integrated by the social and environmental dimensions of the well-being.

The European Commission published the communication: "Not only GDP. Measuring progress in a changing world" in August 2009 [7]. Then, the Commission on the Measurement of Economic Performance and Social Progress (Stiglitz-Sen-Fitoussi Commission) released a report (September 2009) with 12 recommendations for a better social well-being measurement, able to overcome the limitations of standard metrics like GDP [8]. In order to take concrete actions for the sustainable development of each European country, the European Statistical System Committee (ESSC) set up in 2010 a working group to spread and promote the Stiglitz-Sen-Fitoussi Commission's recommendations. To monitor the growth of prosperity at country level in a timely manner, several indices of the union of multiple welfare dimensions' sets were defined [9].

In the current literature, many examples of indices construction and their uses can be surveyed. The Human Development Index (HDI) obtained by health, income, and education dimensions [10] is an example. In the same way, the Environmental Performance Index (EPI) was mainly established on the use of environmental-natural field indicators [11]. Furthermore, Dobrovolskiene et al. [12] developed a composite sustainability index for real estate projects in the Lithuanian context. Attardi et al. [13] proposed the construction of non-compensatory composite indices for the evaluation of environmental and social performances of urban and regional planning policies—Land Use Policy Efficiency Index (LUPEI).

Many of these indices are calculated by considering different well-being dimensions, and by diverse joining-practices. The different type of aggregation pertains to the relative importance weight allocated to each dimension [14–17]. Ravallion [18] proposed an alternative clustering function inspired by that of Chakravarty [19,20], which considers the tradeoffs across the dimensions to be compared with each other [21]. Other studies adopted linear programming tools for the allocation of weights [22–27]. These focus on the simulation of an alternative weight distribution across the well-being dimensions, but not giving significant importance to the relative interactions [28].

Again, Mazziotta and Pareto investigated an operative method to obtain an index by the standard deviation of performance sustainable indicators. However, this methodology also does not consider the interaction among the components [29].

To capture the synergies across the dimensions, the United Nation Development Program (UNDP) from the Arithmetic Mean (AM) aggregation method changed to the Geometric Mean (GM) so that « […] poor performance in any dimension is now directly reflected, and there is no longer perfect substitutability across dimensions» [30]. In this perspective, the using of several methodologies aimed to construct evaluation indices for sustainable assessment is increasing, especially for considering the interactions among the dimensions of the sustainability.

Examples of literature references based on the modeling of the reciprocal relationships between the analysis dimensions of the same decision-making system can be traced in the Decision and Game Theory fields. In them, it noted the application of the Choquet integral proposed in Decision Theory by Schmeidler [31], as an integral with respect to a non-additive probability measure, and later by Murofushi and Sugeno [32], as an integral with respect to a fuzzy measure, using the definition of integral relative to a capacity introduced in 1953 by Choquet [2]. The adoption of the CI for obtaining indices has increased in the XXI century. Meyer and Pontheire [33] showed that preferences by single subjects could not be summarized through an additive model. This was for the complementarities among sustainable dimensions [34–36]. Carraro et al. [37] applied the CI to put in the operative definition of the indices, the interactions across different sustainability indicators. The same was also applied by other authors [38–42]. Most of the literature that adopts the CI aggregation method employs participatory techniques among stakeholders (questionnaire administration, focus group activities, and so on) to identify the weights for the integral implementation [43]. Other examples use the Choquet integral to solve ranking problems [37].

From the testing on indices construction found in the reference literature and at the government level, it is possible to deduce that the aggregation method should be flexible, and it should consider interaction among the analysis dimensions taken into consideration. To allow differing synergies and to choose parameters that identify the unbalanced achievements, this research explores the applicability the Choquet Integral as an alternative aggregation method which captures interactions across analysis fields.

2. Aim

The current work aims to test the applicability of a general aggregation methodology based on the Choquet integral (CI) for the determination of the sustainable composite index to measure the welfare grade at multiple analysis levels, from the country one to that of the neighborhood. The CI considers interactions across sustainable elements of economic, environmental, social type [44], with balanced (or unbalanced) achievements across the dimensions, functional for index construction.

The CI is a general methodology that allows interactions across dimensions while different relative importance (weights) can be assigned to them [45]. In fact, even if the weighted average is the best known and most widely used aggregation operator, it does not adequately perform when the elements to be analyzed have close linkages. Instead, by varying the number of freedom degrees of the Choquet measures (2^n–2) those interactions can be adequately modeled. The Choquet integral consists of a generalization of the weighted mean operator, in which the vector of weights is replaced by a Choquet measure that assigns a value to each element coalition. In this sense, the Choquet integral could be relevant in allowing positive interactions, or synergies, among the sustainable dimensions of analysis that make a general evaluation index constructed in an integrated manner. In this regard, Murofushi and Soneda [46,47] proposed the use of the Shapley value, introduced by Shapley [48] in Game Theory, as an index of relative importance among the factors analyzed. After these prior studies, Grabisch [49] and Roubens [50] provided applications in the Multi-Criteria Decision Theory's field.

The choice of investigating the possibilities arising from the use of the Choquet integrals in the construction of sustainability assessment indices stems from the consideration that they represent a generalization of the best known and most widely used weighted average operators to which the integrals are reduced if the Choquet measures are expressed in additive form.

The paper is organized as follows. Section 3 introduces the CI aggregation method and illustrates its characteristics to highlight the main theoretical-operative features for defining sustainable indices. Particular attention is given to the definition of functional relations among the analysis dimensions of reference with the corresponding weighting assignment and the calculation of three representative indices of the CI methodology—respectively "Relative Importance", "Orness", and "Interaction". Section 4 shows an application of CI methodology by allowing different degrees of interaction across the dimensions of the sustainability with reference to the well-being condition of a set of European countries being considered. In Section 5 the main evidence from the application of the evaluation framework proposed for the construction of indices from the point of view of sustainability is discussed highlighting the most significant academic and practical implications. Section 6 marks the conclusions of the work.

3. The Choquet Integral as Analysis Algorithm for Defining Urban Sustainable Indices

The implementation of the Choquet Integral (CI) for the construction of synthetic valuation indices involves the following Actions (A):

A1 Definition of the set size, i.e., the number of elements that characterize the study set;
A2 Measurement of the importance level (weights) i-th and relative to other components of the analysis set through the Shapley value;
A3 Quantification of Choquet measure for each element of the analysis set considered;
A4 Aggregation level analysis by analytical control factors from Choquet theory (Relative Importance index, Orness index, Interaction index).

In the following, prominence is given to explaining the actions for CI development.

3.1. A1. Identification of Study-Set Size

The CI aggregation method [51,52] is based on the consideration of different inputs from policymakers and private investors possibly involved in the evaluation investment process. This allows political and personal choices to be considered and to frame them within the three dimensions of the sustainability.

Let $\{x_1, x_2, \ldots, x_d\}$ be the decisions values in the sustainable dimensions described by a set of three elements as D = {1, 2, 3}. The «capacities» (μ), i.e., the assigned weights, are defined as utility functions for 2D set, namely for all possible sustainable sub-sets. To each one it is possible to link a weight as expression of the relative importance degree.

The function μ has to satisfy the following conditions:

i. $\mu(0) = 0$; $\mu(D) = 1$;
ii. for any $S, T \subseteq D$, $S \subseteq T \subseteq D \rightarrow \mu(S) \leq \mu(T) \leq \mu(D)$.

The first condition (*i*) represents scenarios where all dimensions are unsatisfactory (all achievements are zero) and respectively satisfactory (the consistency of the capacities is one). The *ii* advises that μ(T) is the weight of dimensions belonging to the sub-set T according to the condition that $T \subseteq D$, which means assigning fully satisfactory performances of the dimensions belonging to T, and unsatisfactory performances to the other dimensions less T. For example, in the case of two or three dimensions, the set ({Dimension1, Dimension2}) will represent the weight attached to the scenario where two achievements are fully satisfactory, and the other one is unsatisfactory.

3.2. A2. Measurement Weights

The μ (i.e., weights to the sub-sets of D) can be identify by several methods and tools as via the literature of reference. As a case of special interest, Grabisch et al. [33] conducted a review with the aim of recognizing the main methods for the capacity's identification such as the: minimum variance, minimum distance, maximum-split, least-squares-based approaches, and so on. All these consider the preferences from decision-makers. Examples of the methods for the elicitation of the capacity are in Meyer and Pontiere, Marichal and Roubens, Bottero et al. [33,42,45]. Bertin et al. [41] defined the weights by minimizing the expert-selection bias. The method of Bertin et al. deletes the potential expert-selection bias if there are many expert-selection involved. Other authors referred to the Shapley function as a fast operative and logical manner for defining weight values related to the capacities.

The Shapley power index (or Shapley value) [52] for each element $i \in N$ ($\theta_\mu^{(i)}$) is utilized by means of the following mathematical expression:

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

The generic Formula (3) can be expressed in another more compact and operational format as in Formula (4):

$$\theta_{\mu}^{(i)} = \frac{1}{|N|!} \sum_{\pi \in \pi_N} \mu(CI(\pi, i) \cup \{i\}) - \mu(CI(\pi, i)) \quad (2)$$

where:

- |N| is the absolute value of the reference dimensions set;
- π_N is the set of all possible orderings of the elements;
- μ (CI (π, i) ∪ {i}) represents the additive value obtained by CI as the sum between the consistency of the i-th reference dimension sub-set and the complementary ones of the same order or greater;
- μ (CI (π, i) measures the consistency of the i-th reference dimension sub-set.

3.3. A3. Quantification of the Choquet Measure

Based on the numerical meaning of $\theta_{\mu}^{(i)}$ it is possible to structure the Choquet measure for each element of the analysis set considered.

Let N = {1, 2, ..., n} be a fixed set of elements that interact with each other. For the element i ∈ N is related to a quantity $x_i \in R$, which seeks to aggregate the quantities $x_i, \dots, x_n \in R$.

Let μ be a Choquet measure on N. Let us define the Choquet integral of the values vector $x = (x_i, \dots, x_n) \in R^n$ the quantity $C_\mu(x)$ as follows:

$$\begin{aligned} C_\mu(x) = \sum_{i=1}^{n} x_{(i)}\left[\mu\left(A_{(i)}\right) - \mu\left(A_{(i+1)}\right)\right] = x_{(i)}\left[\mu\left(A_{(i)}\right) - \mu\left(A_{(i+1)}\right)\right] \\ = \mu\left(A_{(i)}\right)\left[x_{(i)} - x_{(i-1)}\right] \end{aligned} \quad (3)$$

where (·) means a permutation on N.

For N = {1, 2, 3}, the Choquet integral of formula (1) obtains the following algebraic notation:

$$\begin{aligned} C_\mu(x) = x_{(1)}\left[\mu\left(A_{(1)}\right) - \mu\left(A_{(2)}\right)\right] + x_{(2)}\left[\mu\left(A_{(2)}\right) - \mu\left(A_{(3)}\right)\right] \\ + x_{(3)}\left[\mu\left(A_{(3)}\right) - \mu\left(A_{(4)}\right)\right] \\ = x_{(2)}[\mu(231) - \mu(31)] + x_{(3)}[\mu(31) - \mu(1)] \\ + x_{(1)}[\mu(1) - \mu(\emptyset)] \end{aligned} \quad (4)$$

In the following paper the quantity $C_\mu(x)$ is indicated by the simple notation CI.

In the delineated context, this research also aims at outlining how the CI method is capable of capturing the positive interactions by using a set of capacities operating with the *Shapley* function, instead of expert elicitation. This enables the occasion to examine how the trade-off in values across the three sustainable dimensions are functional to the definition of the CI composite scores.

3.4. A4. Aggregation Analysis

Referring to the need to define capacities and the relative weight values through different analysis methods, in this research three important characteristics of the CI are included to illustrate the methodology and its feature to bring in decision-makers' preferences within a sustainable perspective. In particular, the CI can rely on the calculation of three performance indices by which to analyze the effectiveness of the aggregation between the sustainable dimensions in a unique index. They consist of the following: Relative Importance (RI), Orness (O), Interaction (I) indices. As follows, a corresponding explanation is given.

3.4.1. Relative Importance Index

This is related to the Shapley value measurement. The Relative Importance (RI) index is obtained by comparing the weights between each analysis sub-set [46,47]. The importance of dimension $i \in D$ can be obtained by the following formula:

$$v_{\mu}^{(i)} = \sum_{T \subseteq D/i} \frac{(d-1-t)!\,t!}{d!} \left[\mu(T \cup i) - \mu(T)\right] \tag{5}$$

where d = card(D) and t = card(T) are respectively the cardinality of the sub-set of D and T. In a sustainable perspective with reference to economic, social, and environmental dimensions, this would consist of considering four comparisons: (*i*) weight attached to a sub-set that has only social dimension vs. weight attached to an empty sub-set; (*ii*) weight attached to a sub-set that includes social and environmental dimensions vs. weight attached to a sub-set that only includes economic dimension; (*iii*) weight attached to a sub-set that includes social and economic dimensions vs. weight attached to a sub-set that only includes environmental dimension; (*iv*) weight attached to a sub-set that includes all dimensions vs. weight attached to an empty one.

3.4.2. Orness Index

The Orness index is computed as follows:

$$\text{Orness}^{(i)} = \frac{1}{d-1} \sum_{T \subseteq D/i} \frac{d-t}{t+1}\, m(T) \tag{6}$$

where d = card(D) and t = card(T) represents respectively the cardinality of the sub-set of D and T [48]. This index measurement enables the chance to understand if the decision-maker thinks that the dimensions are substitutes (complements) of each other (Orness index is equal to "1"), or not (Orness index is equal to "0").

3.4.3. Interaction Index

Let consider the three dimensions of the sustainability of indices *i*, *j*, and *k*. The interaction index among the three dimensions *i*, *j*, and *k* is by the following expression [49]:

$$I_{\mu}^{(ijk)} = \sum_{T \subseteq D/ijk} \frac{(d-t-3)!\,t!}{(d-1)!} \left[\mu(T \cup ijk) - \mu(T \cup i) - \mu(T \cup j) - \mu(T \cup k) - \mu(T)\right] \tag{7}$$

where d = card(D) and t = card(T) represent the cardinality of sub-sets of D and T, respectively.

In the optic of CI, the quantity $I_{\mu}^{(ijk)}$is a measure of the average marginal interaction among i,,j, and k. The $I_{\mu}^{(ijk)}$ must be ∈ [−1, 1] for all i,j,k ⊆ D. The value "1" (respectively "−1") is referred to the maximum complementariness among i, j, and k [50]. The interaction index among the dimensions i, j, and k can be rewritten also as follows:

$$I_{\mu}^{(ijk)} = \sum_{T \subseteq D/i} \frac{1}{t+1}\, m(T \cup ijk) \tag{8}$$

4. Case Study

In order to test the feasibility of using the Choquet integral as an innovative (or alternative) method for defining evaluation indices based on the interaction among the three dimensions of the sustainability, a study set of 24 European countries was considered. By the implementation of the CI method referring to European countries, the intent was to develop the Choquet integral aggregation method for obtaining evaluation scores that represent the sustainable level at country level. This takes into account the sustainable dimensions—economic, social, and environmental type—by means of appropriate performance indicators. The development of the proposed Choquet integral allows the ranking problem to be solved at territorial scale between countries evaluated with each other under the sustainable point of view. The score by CI method is then compared to that one obtained with the GM and AM process. This application and subsequent comparison among CI, GM, and AM will illustrate the effectiveness of the Choquet integral for structuring indices able to support the evaluation processes of the sustainability at country level. Subsequently we retrace the operational actions that characterize the development of the Choquet integral (see Section 3) with regard to the explored case study.

4.1. A1. Identification of Study-Set Size

Each European country considered to test the implementation of the CI method is evaluated according to the economic, social, and environmental dimensions, in particular, using the proper performance indicator as an expression of each sustainable field. The value of the performance indicator at each country is extracted by the online platform of the OECD available at the corresponding website free of charge (last accessed 15 January 2022). Data are referred to the year 2020. From the OECD database it is possible to detect the requested information on 24 countries (1. Austria; 2. Belgium; 3. Czech Republic (CR); 4. Denmark; 5. Estonia; 6. France; 7. Germany; 8. Greece; 9. Ireland; 10. Italy; 11. Latvia; 12. Lithuania; 13. Luxembourg; 14. Netherlands; 15. Norway; 16. Poland; 17. Portugal; 18. Slovak Republic (SR); 19. Slovenia; 20. Spain; 21. Sweden; 22. Switzerland; 23. Turkey; 24. United Kingdom), referred to the year 2020.
Specifically, the parameters representative of the multiple sustainable dimensions for each European country are reported in Table 1 and described as follows:

1. Social Connection (SC), that is measured by the share of people answering “yes” to a (yes/no) question: “If you were in trouble, would you have relatives or friends you can count on to help you whenever you need them, or not?”. The data come from the Gallup World Poll database, which collects information on approximately 1000 people per country per year. The sample is believed to be nationally representative of the population 15 years of age or older;
2. Real GDP per capita (RGDP);
3. Median Surface of accessible Green urban areas (MSG), as the quantity of green surfaces utilized by a population of 1000 inhabitants.

Countries for which the value of one of the indicators considered is missing were excluded from the study-set of analysis, in order to make a comparison between alternatives as homogeneous and rigorous as possible. From a starting group of 24 countries, a sub-set of 20 is taken as the basis of the case study. A group of 20 countries is obtained excluding Greece, Luxembourg, Turkey, United Kingdom. In view of the aggregative score via the CI method, each sustainable dimension must be comparable in terms of the value range of the corresponding data set. So, the values of Table 1 are normalized with “max-min” technique, obtaining the outcomes of Table 2.

Table 1. European countries data set.

Country		SC	RGDP	MSG
		[%]	[€ per Capita]	[ha]
1.	Austria	7.51	35,390	15.77
2.	Belgium	9.58	33,560	15.38
3.	Czech Republic (CR)	3.59	17,340	41.39
4.	Denmark	5.25	48,150	14.33
5.	Estonia	4.19	15,010	28.88
6.	France	5.25	30,610	10.71
7.	Germany	9.45	34,310	20.76
8.	Ireland	3.97	62,980	8.83

9.	Italy	11.00	24,890	7.35
10.	Latvia	7.14	12,150	22.87
11.	Lithuania	4.42	14,030	47.51
12.	Netherlands	5.58	40,160	19.96
13.	Norway	4.40	68,630	27.59
14.	Poland	4.62	12,700	19.98
15.	Portugal	12.45	17,070	7.81
16.	Slovak Republic (SR)	4.56	15,180	19.65
17.	Slovenia	4.64	19,720	14.39
18.	Spain	6.51	22,350	12.49
19.	Sweden	6.44	42,640	61.02
20.	Switzerland	5.35	60,820	18.55

Table 2. Normalized data set.

		SC	RGDP	MSG
1.	Austria	0.34	0.43	0.26
2.	Belgium	0.43	0.41	0.25
3.	CR	0.16	0.21	0.68
4.	Denmark	0.24	0.59	0.23
5.	Estonia	0.19	0.18	0.47
6.	France	0.24	0.37	0.18
7.	Germany	0.43	0.42	0.34
8.	Ireland	0.18	0.77	0.14
9.	Italy	0.50	0.30	0.12
10.	Latvia	0.32	0.15	0.37
11.	Lithuania	0.20	0.17	0.78
12.	Netherlands	0.25	0.49	0.33
13.	Norway	0.20	0.83	0.45
14.	Poland	0.21	0.15	0.33
15.	Portugal	0.56	0.21	0.13
16.	SR	0.21	0.18	0.32
17.	Slovenia	0.21	0.24	0.24
18.	Spain	0.29	0.27	0.20
19.	Sweden	0.29	0.52	1.00
20.	Switzerland	0.24	0.74	0.30

4.2. A2. Measurement Weights

Taking into account the Table 2 data, the next step is the characterization of the CI method to the case study, therefore the weights-capacities for the CI aggregation are defined. They express the different degrees of positive interactions among sustainable dimensions [50]. By {SC, RGD, MSG}, six sub-sets can be extracted: ({SC}), ({RGDP}), ({MSG}), ({SC, RGDP}), ({SC, MSG}), ({RGDP, MSG}). Table 3 displays the Choquet integral capacities and the weights related to each sub-set. The values of Table 3 are achieved when μ {SC}, μ {RGDP}, μ {MSG} are considered together, namely their consistency value is equal to one.

In operative terms, via Formula (2) of Section 3, i.e., {RGDP} has the following features:

$$\theta_{\mu}^{(\mathrm{RGDP})} = \frac{\left[\left(\mu(\{\mathrm{RGDP}\} \cup \{\mathrm{SC}\}) - v(\{\mathrm{RGDP}\})\right) + \left(\mu(\{\mathrm{RGDP}, \mathrm{MSG}\} \cup \{\mathrm{SC}\}) - \mu(\{\mathrm{RGDP}, \mathrm{MSG}\})\right)\right]}{|N|!}$$

Likewise, for the other single sub-sets and related combinations.

By Equation (2) it is possible to make also multiple weights-sets values depending on the decision maker preferences. In specific terms, the set of different interaction degrees among sustainable dimensions defines decision-making scenario alternatives (CI_i) where in each one the pair of sustainable dimensions are considered either together or separately. In Table 4 weights-capacities sets are reported in accordance to different $\mu(CI(\pi, i)$. Specifically, by considering a set constituted by three dimension fields {SC, RGDP, MSG}, six $\mu(CI(\pi, i)$ alternatives are established by assigning the value "1" to {SC}, {RGDP}, {MSG} individually and to their couple {SC, RGDP}, {SC, MSG}, {RGDP,MSG}.

Table 3. CI_0 weights-capacities.

Sub-Sets (*i*)	$\|N\|!$	**CI_0**	
		$\mu(CI(\pi, i))$	$\theta(i, v)$
{SC}		1	0.33
{RGDP}		1	0.33
{MSG}	6	1	0.33
{SC, RGDP}		2	0.67
{SC, MSG}		2	0.67
{RGDP, MSG}		2	0.67

Table 4. Sets of CI weights-capacities for six different sub-sets combinations.

	CI_1		**CI_2**		**CI_3**		**CI_4**		**CI_5**		**CI_6**	
Sub-Sets (i)	$\mu(CI(\pi, i))_1$	$\theta(i, \mu)_1$	$\mu(CI(\pi, i))_2$	$\theta(i, \mu)_2$	$\mu(CI(\pi, i))_3$	$\theta(i, \mu)_3$	$\mu(CI(\pi, i))_4$	$\theta(i, \mu)_4$	$\mu(CI(\pi, i))_5$	$\theta(i, \mu)_5$	$\mu(CI(\pi, i))_6$	$\theta(i, \mu)_6$
{SC}	1	0.33	0	0	0	0	1	0.33	1	0.33	0	0
{RGDP}	0	0.33	1	0	0	0	1	0.33	0	0.33	1	0
{MSG}	0	0.33	0	0	1	0	0	0.33	1	0.33	1	0
{SC, RGDP}	1	0.33	1	0.33	0	0	2	0.67	1	0.33	1	0.33
{SC, MSG}	1	0.33	0	0	1	0.33	1	0.33	2	0.67	1	0.33
{RGDP, MSG}	0	0.00	1	0.33	0	0	0	0	0	0	2	0.67

4.3. *A3. Quantification of the Choquet Measure*

The composite scores via the Choquet integral aggregation for each European country are obtained by using the capacities (weights) from Tables 3 and 4 as follows :({SC}) × SC + ({RGDP}) × RGDP+ ({MSG}) × MSG + [({SC, RGDP}) − ({SC}) − ({RGDP})] × min (SC, RGDP) + [({SC, MSG}) − ({SC}) − ({MSG})] × min (SC, MSG) + [({RGDP, MSG}) − ({RGDP}) − ({MSG})] × min (RGDP, MSG) + [1 − ({SC, RGDP}) − ({RGDP, MSG}) − ({RGDP, MSG}) + ({SC}) + ({RGDP}) + ({MSG})] × min (SC, RGDP, MSG). In Table 5 the composite score of 24 European countries for the Choquet integral capacities cases are reported. The CI scores are functional to the definition of the average CI value ($\overline{CI}$), on the basis of which it is possible to compare the outcomes related to CI, GM, and AM. The final outputs are in Table 6.

Table 5. CI scores for European countries of study.

	Country	**SC**	**RGDP**	**MSG**	**CI_0**	**CI_1**	**CI_2**	**CI_3**	**CI_4**	**CI_5**	**CI_6**	**$\overline{CI}$**
		[%]	[€ per Capita]	[ha]								
1.	Austria	7.51	35,390	15.77	0.3426	0.3158	0.2854	0.2585	0.3426	0.3158	0.2854	0.3005
2.	Belgium	9.58	33,560	15.38	0.3643	0.3123	0.3040	0.2520	0.3643	0.3123	0.3040	0.3081

3.	CR	3.59	17,340	41.39	0.3505	0.3181	0.1784	0.1622	0.3181	0.3181	0.1946	0.2442
4.	Denmark	5.25	48,150	14.33	0.3525	0.3517	0.2357	0.2348	0.3525	0.3517	0.2357	0.2936
5.	Estonia	4.19	15,010	28.88	0.2817	0.2795	0.1825	0.1847	0.2795	0.2817	0.1847	0.2315
6.	France	5.25	30,610	10.71	0.2616	0.2411	0.1960	0.1756	0.2616	0.2411	0.1960	0.2185
7.	Germany	9.45	34,310	20.76	0.3947	0.3691	0.3659	0.3403	0.3947	0.3691	0.3659	0.1095
8.	Ireland	3.97	62,980	8.83	0.3633	0.3518	0.1563	0.1448	0.3633	0.3518	0.1563	0.2540
9.	Italy	11.00	24,890	7.35	0.3067	0.2459	0.1812	0.1205	0.3067	0.2459	0.1812	0.2135
10.	Latvia	7.14	12,150	22.87	0.2816	0.2234	0.1477	0.2060	0.2234	0.2816	0.2060	0.2001
11.	Lithuania	4.42	14,030	47.51	0.3829	0.3733	0.1706	0.1802	0.3733	0.3829	0.1802	0.2743
12.	Netherlands	5.58	40,160	19.96	0.3559	0.3058	0.2772	0.2521	0.3058	0.3058	0.3022	0.2852
13.	Norway	4.40	68,630	27.59	0.4952	0.3263	0.2833	0.1989	0.3263	0.3263	0.3678	0.2837
14.	Poland	4.62	12,700	19.98	0.2301	0.2121	0.1544	0.1725	0.2121	0.2301	0.1725	0.1877
15.	Portugal	12.45	17,070	7.81	0.2993	0.2729	0.1546	0.1281	0.2993	0.2729	0.1546	0.2137
16.	SR	4.56	15,180	19.65	0.2375	0.2304	0.1846	0.1917	0.2304	0.2375	0.1917	0.2092
17.	Slovenia	4.64	19,720	14.39	0.2284	0.2110	0.2184	0.2097	0.2110	0.2110	0.2271	0.2125
18.	Spain	6.51	22,350	12.49	0.2568	0.2345	0.2271	0.2047	0.2568	0.2345	0.2271	0.2307
19.	Sweden	6.44	42,640	61.02	0.6031	0.4514	0.3667	0.2909	0.4514	0.4514	0.4426	0.3901
20.	Switzerland	5.35	60,820	18.55	0.4284	0.3870	0.2626	0.2419	0.3870	0.3870	0.2833	0.3196

Table 6. Scores with the $\overline{CI}$, GM, AM.

Country		$\overline{CI}$	GM	AM
1.	Austria	0.3005	0.34	0.34
2.	Belgium	0.3081	0.35	0.36
3.	CR	0.2442	0.29	0.35
4.	Denmark	0.2936	0.32	0.35
5.	Estonia	0.2315	0.25	0.28
6.	France	0.2185	0.25	0.26
7.	Germany	0.1095	0.39	0.39
8.	Ireland	0.2540	0.27	0.36
9.	Italy	0.2135	0.26	0.31
10.	Latvia	0.2001	0.26	0.28
11.	Lithuania	0.2743	0.30	0.38
12.	Netherlands	0.2852	0.34	0.36
13.	Norway	0.2837	0.42	0.50
14.	Poland	0.1877	0.22	0.23
15.	Portugal	0.2137	0.25	0.30
16.	SR	0.2092	0.23	0.24
17.	Slovenia	0.2125	0.23	0.23
18.	Spain	0.2307	0.25	0.26
19.	Sweden	0.3901	0.53	0.60
20.	Switzerland	0.3196	0.38	0.43

4.4. A4. Aggregation Analysis

The Interaction and Orness indices are of reference in the case of the maximum set size of three dimensions as stated by Pinar [52]. They are reported in Table 7, respectively equal to 0.35 and 0.15. This output suggests that the dimensions manifest some degree of complementarity (synergy). Instead, the Relative importance index is associated to the Shapley value of each dimension and relative association. It corresponds to the values of Table 4 as in A3 action explanation.

Table 7. Interaction indices and Orness index of reference.

	Interaction Indices
{SC, RGDP, MSG}	0.35
	Orness Index
{SC, RGDP, MSG}	0.15

5. Discussion

By CI, GM, and AM an evaluation score is extracted (see Table 6). This expresses the sustainable performance level of each country. From the results of Table 6, the use of CI attempts to favor the unbalanced achievements among the sustainable dimensions. The GM and AM aggregation methods offer equal composite scores for some European countries (Sweden, Norway, Italy, Estonia, Spain, SR). With GM-AM processes, countries with unbalanced achievements across dimensions can have similar scores. For instance, by means of the GM and AM list, some countries that differ significantly in socio-economic and environmental terms are comparable in having the same score which is the case of Estonia, France, and Spain, with a GM evaluation score equal to 0.25, and CR, Denmark, with an AM evaluation score amounting to 0.35. They have similar composite scores despite having unbalanced achievements across sustainable dimensions.

Therefore, as stated by the UNDP on the importance of accounting the non-substitutability across dimensions [30], the CI method meets the 2010 UNDP report's aims by successfully accounting for balanced and unbalanced achievements across the sustainable dimensions and allowing different degrees of interaction between them. When using the CI method, countries with unbalanced achievements across dimensions can be penalized with lower rankings compared to the GM and AM methods. The CI method rewards balanced achievements across dimensions by ranking those countries higher [53–58].

To demonstrate the above, the final ranking lists were realized. Table 8 shows the countries' lists according to the average CI score, and that obtained also via the GM and AM aggregation methods. In the same Table 8 the ranking list according to the SC, RGDP, and MSG value are shown.

Considering, e.g., the Belgium position with respect to the key-performance indicators (SC, RGDP, MSG) and the one obtained by the aggregation method (CI, GM, AM), the country considered vacates positions 3, 9, 13 under SC, RGDP, MSG; under GM and AM 5 and 6 position, while under CI it is in third position. By this, the aggregation using the CI methodology can be affected by the relative position of the individual country with respect to each performance indicator value. This is hardly recognizable compared to what can be obtained with GM and AM where the evaluation score is based significantly on the max and min values of the indicator-sets. From the priority lists one can also detect cases of perfect coincidence between the out-puts obtained by the three aggregation methods, as in the case of Sweden in first position for CI, GM, and AM. This demonstrates that the Choquet integrals represent a generalization of the best known and most widely used weighted average operators to which they are reduced if the Choquet measures are additive. What distinguishes Choquet integrals as aggregation operators from weighted average operators is their usefulness in the presence of interacting elements.

The definition of an evaluation index with the CI method allows the taking into account of the effective social, economic, and environmental imbalances of each territory examined. This leads to interesting and significant implications in terms of evaluating the sustainable performance, especially for the identification of the political-urban realities to be prioritized in terms of sustainable investments. The priority list of 20 European countries obtained via CI could be taken as a reference in the need of allocating financial resources among member countries in order to support the sustainable development of countries with unbalanced realities, and also in view of intergenerational equity. Taking the priority list generated through the CI method, this would offer the opportunity to favor the improvement of territorial realities, considering existing socio-economic and environmental inequalities, and not only the main performing aspects. In this regard, taking Norway as an example, in GM and AM it is in second position, while in CI it is 7, despite having the highest RGDP value. This is in light of the inconsistencies in values from an economic, social, and environmental sustainability perspective.

Table 8. Ranking lists of the 20 European countries

	SC	RGDP	MSG	$\overline{\mathrm{CI}}$	GM	AM
1	Portugal	Norway	Sweden	Sweden	Sweden	Sweden
2	Italy	Ireland	Lithuania	Switzerland	Norway	Norway
3	Belgium	Switzerland	CR	Belgium	Germany	Switzerland
4	Germany	Denmark	Estonia	Austria	Switzerland	Germany
5	Austria	Sweden	Norway	Denmark	Belgium	Lithuania
6	Latvia	Netherlands	Latvia	Netherlands	Austria	Belgium
7	Spain	Austria	Germany	Norway	Netherlands	Ireland
8	Sweden	Germany	Poland	Lithuania	Denmark	Netherlands
9	Netherlands	Belgium	Netherlands	Ireland	Lithuania	CR
10	Switzerland	France	SR	CR	CR	Denmark
11	Denmark	Italy	Switzerland	Estonia	Ireland	Austria
12	France	Spain	Austria	Spain	Italy	Italy
13	Slovenia	Slovenia	Belgium	France	Latvia	Portugal
14	Poland	CR	Slovenia	Portugal	Estonia	Estonia
15	SR	Portugal	Denmark	Italy	France	Latvia
16	Lithuania	SR	Spain	Slovenia	Portugal	France
17	Norway	Estonia	France	SR	Spain	Spain
18	Estonia	Lithuania	Ireland	Latvia	SR	SR
19	Ireland	Poland	Portugal	Poland	Slovenia	Poland
20	CR	Latvia	Italy	Germany	Poland	Slovenia

6. Conclusions

The assessment of the level of sustainability on a territorial scale requires the use of methodologies and tools that allow public decision-makers to include it in the political and territorial planning choices. In the planning field, the adoption of indices is necessary that allow the evaluation of the projects considering the integration between the aspects of economic, social, and environmental sustainability. In fact, the use of indices allows the knowledge of the intervention context to be improved, and it facilitates the identification of sustainable design solutions consistent with the 17 SDGs (United Nations Agenda 2030) and the European Green New Deal strategy.

Methodologies and tools of economic evaluation are essential in the process of choosing the "best" alternatives as they allow proper consideration of the many aspects of sustainability, and also the effects generated by the intervention in the context of reference. These strategical choices can be supported using evaluation indices that take into account the multiple relationships among the different dimensions of sustainability.

Therefore, this research proposed an application of the Choquet integral as a flexible method to support the definition of evaluation indices based on the different degree of interaction among the dimensions of sustainability at the territorial scale. The proposed application outlined that the Choquet integral allows different degrees of positive interactions among pairs of sustainable fields to be accounted for. This is in distinction to the more widely used methods of GM and AM. The Choquet methodology allows the preferences of policymakers and public entities to be reflected, by adopting different preference sets, including a variety of interaction levels across pairs of dimensions (e.g., considering some of the well-being dimensions to be substitutes and others to be complements) and different relative importance degree (i.e., higher or lower Shapley values).

Borrowing the logic of the Shapley function for the definition of the weights, the proposed methodology can take into account varying positive interactions, highlighting the usefulness of the Choquet aggregation methodology in capturing the functional links across the sustainable dimensions.

It is important to highlight that the preferability of the proposed CI method for the construction of an evaluation index should be decided by the decision-makers involved according to the following: (i) established sustainable objectives; (ii) data availability for the spatial scale considered; (iii) willingness, in terms of importance for the final objectives, to consider or not the interactions among indicators; (iv) the skills of the final users, unless it is possible to use software for CI implementation.

Future insights will concern the verification of the advantages and limits of the proposed approach in the following: (i) analysis of the interactions among sustainable indicators through the involvement of experts' elicitation for the urban scale contexts, and (ii) the inclusion of more performance indicators related to investment projects for the urban sustainable growth of the city.

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