A Methodological Approach Based on the Choquet Integral for Sustainable Valuations

Francesco Tajani[1], Francesco Sica[2], Maria Rosaria Guarini[1], Pierluigi Morano[3], and Rossana Ranieri[1](✉)

[1] Department of Architecture and Design, "Sapienza" University of Rome, 00196 Rome, Italy
rossana.ranieri@uniroma1.it

[2] Department of Civil, Environmental and Mechanical Engineering, University of Trento, 38123 Trento, Italy

[3] Department of Civil, Environmental, Land, Building Engineering and Chemistry (DI-CATECh), Polytechnic University of Bari, 70126 Bari, Italy

Abstract. Several methods and operational tools for assessing the sustainability and corresponding aspects can be identified in the current literature. At international level, the use of synthetic indices is clearly established through analytical indicators capable of expressing multiple aspects from an economic, social and environmental perspective. By a literature review, the construction of indices through a multi-criteria approach can be placed in the weights assignment and in construction processes based on the geometric and arithmetic average of values. The allocation of appropriate weights to performance indicators lacks, in particular, an objective methodology and subjective elements linked, e.g., to the decision-makers involved and corresponding interests. This research aims to describe a methodological frame for indices constructing through the multi-criteria approach of the Choquet Integral. The use of Choquet's integral supports the evaluations of multiple aspects of sustainability as monitoring of the relative unbalanced values, and the weights assignment occurs through analytical functions well-established, as the Shapley function.

Keywords: Sustainable index · Choquet integral · Multi-criteria approaches · Territorial investments · 2030 Agenda

1 Introduction

The sustainable assessment of urban networks in changing perspective has become a central issue for the development and implementation of effective planning strategies. In world-wide context, the political agenda has been rating the impacts of sustainable investments on citizens' well-being, environmental quality, economic growth within the decision-systems for territories growing. The well-being "sustainable foot-print" at territorial and urban scale steers to revise the income by integrating multiple aspects, also related to the society and environment [1–4].

O. Gervasi et al. (Eds.): ICCSA 2022 Workshops, LNCS 13381, pp. 3–14, 2022.
https://doi.org/10.1007/978-3-031-10548-7_1

In light of this, the use of Gross Domestic Product (GDP) as an effective representative measure of the urban/territorial well-being is becoming less obvious in economic terms too. The limits of GDP are recognized in the inability to distinguish among events that could have positive and negative impacts on well-being – e.g., reconstruction following a natural disaster or war –, so to appear an effective indicator that summarizes a country's economic activity in a comprehensive manner, not in view of environmental impacts, working conditions, health, and human-social capital.

An analysis of the current literature revealed several research focused on alternative quantification of well-being, quality of life, sustainable development and societal progress. Namely, alternative methodological approaches to GDP have been defined [5]. To date (2022), the "Istanbul Declaration" - signed by the European Commission, the Organization of the Islamic Conference, the United Nations, the United Nations Development Program (UNDP) and the World Bank in June 2007, at the end of the 2nd Organization for Economic Co-operation and Development World Forum - has stated that there is the need to go "beyond GDP" for assessing the well-being at scale of territory and city [6–9].

Methodological approaches to measure the progress of a society with relative well-being state are advisable in the reference literature. There is search for methods and tools aimed to integrate financial values with social and environmental items not detected in GDP [10]. With a view to moving beyond the use of GDP as the main performance indicator for expressing the well-being state, alternative composite indices have been proposed to enable the societal welfare declined in the dimensions of the sustainability (economic, social and environmental) [11].

The UNDP implements the Human Development Index (HDI), which considers health, income and education information data [12]. Similarly, the Environmental Performance Index (EPI) is developed based on primarily environmental-natural indicators [13]. Dobrovolskiene et al. (2017) in the specific Lithuanian context, develop a composite index to verify the sustainability of real estate projects [14], and Attardi et al. propose the Land Use Policy Efficiency Index for the assessment of the environmental and social performance of urban and regional planning policies [15]. Many of these are obtained by aggregating weighted averages related to the different dimensions of well-being, in such a way as to express the appropriate weight for each dimension [16–20]. Furthermore, Ravallion proposes an alternative aggregation function based on the generalized aggregation formula of Chakravarty [21, 22], which allows for a more effective weighting of dimensions than geometric mean [23]. On the other hand, further studies analyze the strength of weights by implementing linear programming processes capable of evaluating the accuracy of rankings with alternative weights [24–29]. These works do not consider the potential interaction among dimensions, but focus on the impact of alternative weight allocation among well-being dimensions on ranking accuracy.

In order to attempt to express particular sustainable statement with specific indices of environmental, social and economic nature, the current research work proposes the adoption of a method of aggregation - the Choquet Integral (CI) - capable of considering the synergies among the sustainable dimensions for the construction of evaluation indices [30]. The CI has been developed by Murufushi and Sugeno as a powerful aggregation operator over an established set of elements [31], and it has been used in selection cases, particularly attracting the fuzzy principles. A critical issue encountered in the application of fuzzy measures consists in the exponential complexity in terms of real number for each subset of the criteria and means to evaluate these through appropriate elicitation of interviewed experts or optimization methods [32, 33]. In this sense, Mazziotta and Pareto (2016) propose the structuring of a method to calculate a non-compensatory index, which penalizes the unbalanced values of indicators through the relative standard deviation measurement [34].

In order to capture synergies among dimensions for an index construction, the UNDP moved from the Arithmetic Mean (AM) to the Geometric one (GM) [12]. However, the GM aggregation method doesn't allow to capture the complementarity and synergies among dimensions. A relatively weak performance in one of the dimensions is counted similarly in the composite score obtained. Compared to the UNDP experimentation, the proposed methodological approach develops an alternative and flexible aggregation process able to perceive a set of interactions among the sustainable dimensions, in order to allow different synergies and to detect unbalanced performance among them.

The use and implementation of the CI for obtaining multivariate and composite indices improved in recent years. E.g., Meyer and Pontheire [37] have employed the CI to show that individual preferences could not be effectively described by an additive model (i.e., weighted average aggregation methods) because of com-plementarities and redundancies among analysis dimensions [38–40]. Many of the other authors take advantage of the CI in the optic to assemble indices that allow different interactions among indicators [41–46], namely Campagnolo et al. [47] applied the CI aggregation method to capture interactions across diverse sustainable factors.

1.1 Aim

The research carried out develops a methodology based on the CI, in order to establish a composite index that could be used: *i*) to assess, from a macro-economic point of view, a well-being level of a country and/or its sub-scale; *ii*) to value, from a micro-economic one, the sustainability of territorial investments. The CI is a general methodology that allows interactions across dimensions (economic, environmental, social) while allocating different relative importance to them. This allows to consider if and how balanced (or unbalanced) the accomplishments across dimensions are and to reveal these differences in the composite score [35, 36].

The paper is organized as follows: in Sect. 2, the methodological approach is illustrated; in Sect. 3, a brief discussion about the CI highlights is reported; in Sect. 4, the conclusions of the research are drawn.

2 Methodological Approach

2.1 Overview

The CI aggregation method [30] is able to support multiple decision-making processes thanks to its ability to collect and synthesize different inputs. Figure 1 describes the four steps of the logical protocol that defines the methodology.

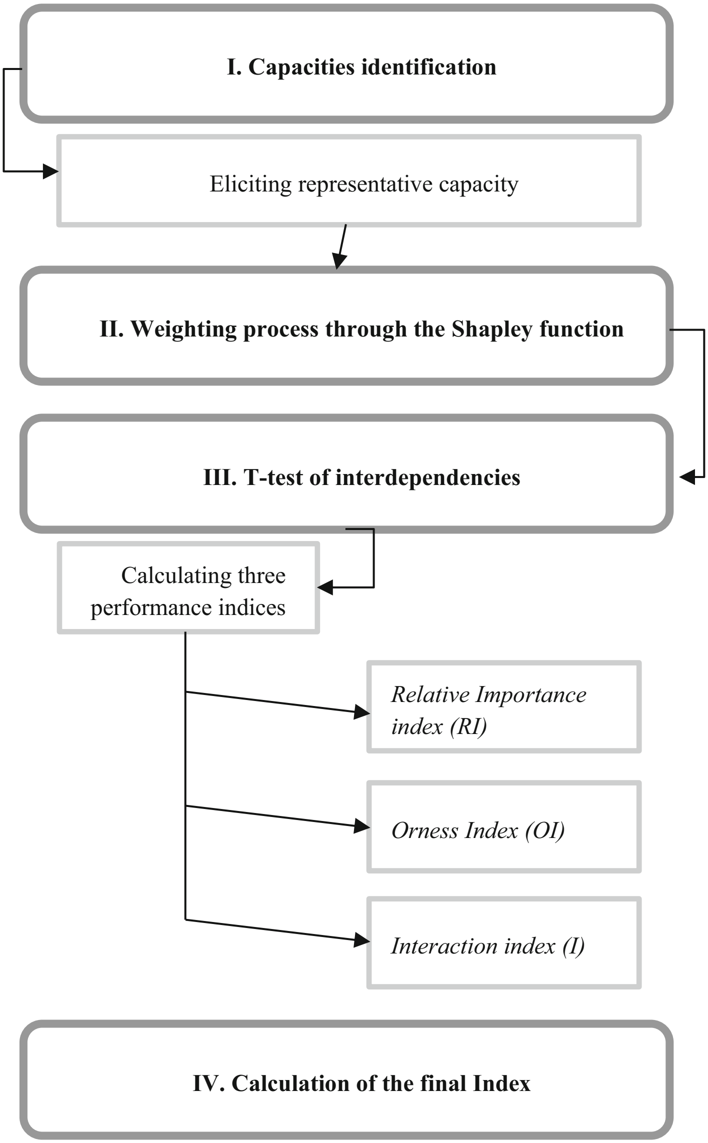

Fig. 1. Logical protocol summary chart for structuring the methodology

Let $\{n_1, n_2, \ldots, n_d\}$ be the values of the dimensions described by a set $T = \{1, 2, 3\}$. The «capacities» are a set of functions where 2T is all possible subsets of the criteria, which assigns a weight from 0 to 1 to each one.

The set function (λ) has to satisfy border and monotonicity conditions as described hereafter:

i. λ (0) = 0; $\lambda(T) = 1$;
ii. for any A, B $\subseteq$ T, A $\subseteq$ B $\subseteq$ T $\rightarrow$ $\lambda(A) \leq \lambda(B) \leq \lambda(T)$.

The *i*) characterizes scenarios in which all dimensions are - respectively - unsatisfactory (i.e., achievements in all dimensions are zero) and satisfactory (i.e., achievements in all dimensions are full). The *ii*) implies that the value of λ(A) signifies the capacity (weight) of dimensions belonging to the subset A in T. This can be interpreted as the weight (importance) that one assigns to the fully satisfactory performances of the dimensions belonging to the subset A, and with fully unsatisfactory performances by the residual dimensions.

Specifically, if a subset has two out of three dimensions, then ({Dimension1, Dimension2}) would signify the weight assigned to the scenario where two-dimension achievements are fully satisfactory, and the other one is fully unsatisfactory.

2.2 Capacities Identification

The CI methodology firstly requires to identify the set of capacities. Though, eliciting representative capacity (monotonic weight sets) for the CI method is quite complex task because of the difficulties in identifying the specific issue to be investigated.

Many identifications methods in the current scientific literature have been elaborated by an optimization problem where restrictions are obtained from the preferences of the decision-makers involved. A review of methods employed for the identification of capacities (i.e. maximum-split, minimum variance, minimum distance, least-squares-based approaches) has been carried out by Grabisch et al. [48]. Other examples to be considered in this phase of the construction of the methodology [49] specify how to elicit capacity by representing decision-makers' preferences. Additionally, Bertin et al. [43] have elicited weights and parameters using a nominal group computer-based technique to reduce the severely disagreeing valuations, to generate an *ex-post* consensus and to mitigate the potential expert-selection bias. The expert elicitation method adapted by Bertin et al. [43] is an effective method to reduce the potential expert-selection bias; however, supposing the most expert selection involves high bias levels, the method adopted may not lessen the potential expert-selection bias, whereas it could increase such bias as the consensus weights are closer to the ones selected by the majority of the experts.

2.3 Weighting Process Within the Choquet Integral

In addition to the need to define capabilities, three important features of the CI must be defined to effectively describe the flexibility of the methodology, in order to include decision-maker preferences in assessments related to multiple aspects of well-being from a sustainable perspective. The CI weighting process is based on the calculation of three different performance indices that allow for consideration of the value of the weight of the assessment domains, specifically indices of: Relative Importance (RI), Orness (OI), Interaction (I). An explanation is given as follows for each index.

Relative Importance Index (RI)

The RI of sustainable dimensions can be assessed using the Shapley value (s_λ) [50] of each dimension, calculated by comparing the weights in every set that includes that dimension against every set that does not include it. Therefore, the overall importance of dimension $i \in \mathrm{T}$ can be gained by calculating the average marginal contributions [51, 52] as follows:

$$s_\lambda^{(i)} = \sum_{\mathrm{A} \subseteq \mathrm{T}/i} \frac{(t-1-a)!a!}{a!}[\lambda(\mathrm{A} \cup i) - \lambda(\mathrm{A})]$$

where t = card(T) and a = card(A) represent the cardinality of A and T. Hence, to obtain the importance of a single dimension it is possible to compare the weights assigned to subsets that include the single dimension, with the subsets that do not have the dimension considered. In sustainable perspective, with reference to economic, social and environmental dimensions, this would consist of four comparisons: *i*) weight attached to a subset that has social dimension only vs. weight attached to an empty subset; *ii*) weight attached to a subset that includes social and environmental dimensions vs. weight attached to a subset that only includes economic dimension; *iii*) weight attached to a subset that includes social and economic dimensions vs. weight attached to a subset that only includes environmental dimension; *iv*) weight attached to a subset that includes all dimensions vs. weight attached to a subset that includes social and economic dimensions.

In terms of the Möbius representation [53] (m) of λ, the Shapley value of dimension i can be expressed as follows:

$$s_\lambda^{(i)} = \sum_{\mathrm{A} \subseteq \mathrm{T}/i} \frac{1}{a+1}[m(\mathrm{A} \cup i)]$$

It is necessary to point out that, the specific importance of the dimensions (i.e., Shapley values) sums to one ($\sum_{i=1}^{d} s_\lambda^{(i)} = 1$), and higher Shapley values represent higher relative importance.

Orness Index (OI)

The CI aggregation also permits to define if the choice of the weights by the decision-maker is optimistic or pessimistic [54]. In other words, the OI determines if a decision-maker assumes that a good performance in one dimension balances another one or not. The OI varies between 0 and 1, and higher (lower) values of this index represent that the decision-maker thinks that the dimensions are substitutes (complements) of each other. In particular, if OI equals to 1, the decision-maker judges a fully compensative situation and, in this case, CI aggregation will be equal to the maximum operator. Otherwise, if OI is equal to 0, then the decision-maker considers a fully non-compensative situation, and the CI corresponds to the minimum operator (i.e., the dimensions are perfect complements), and the index outcome would be the lowest value amongst the dimensions. The OI is calculated as follows:

$$OI^{(i)} = \frac{1}{a-1} \sum_{\mathrm{A} \subseteq \mathrm{T}/i} \frac{t-a}{a+1} m(\mathrm{A})$$

where t = card(T) and a = card (A) correspond to the cardinality of the subset of T and A.

<u>Interaction Index (I)</u>
The main reason for using the CI to structure a composite index is the ability of CI to consider the interaction and the synergies among sustainable dimensions. Taken the three dimensions of the sustainability of i, j and k, an average Interaction index (I) among the three dimensions i, j and k is determined as follows [55]:

$$I_{\lambda}^{(ijk)} = \sum_{\mathrm{A} \subseteq \mathrm{T}/ijk} \frac{(t-a-3)!a!}{(t-1)!} [\lambda(\mathrm{A} \cup ijk) - \lambda(\mathrm{A} \cup \mathrm{i}) - \lambda(\mathrm{A} \cup \mathrm{j}) - \lambda(\mathrm{A} \cup \mathrm{k}) - \lambda(\mathrm{T})]$$

where t = card(D) and a = card (A) represent, respectively, the cardinality of A and T.

The quantity $I_{\lambda}^{(ijk)}$ can be explained as a measure of the average marginal interaction among i, j and k. An important property is that $I_{\lambda}^{(ijk)} \in [-1, 1]$ for all $ijk \subseteq$ T. The value 1 (respectively −1) corresponding to maximum complementarity, and not, among i, j and k [56]. In terms of the Möbius (m) representation [53] of $I_{\lambda}^{(ijk)}$, the interaction index between the three dimensions i, j and k can be rewritten as:

$$I_{\lambda}^{(ijk)} = \sum_{\mathrm{A} \subseteq \mathrm{T}/i} \frac{1}{a+1} m(\mathrm{A} \cup ijk)$$

3 Highlights of the Choquet Integral for Indices Construction

CI turns out to be an alternative method for defining evaluation indices based on the interaction among the three dimensions of sustainability. The proposed methodological approach takes into account the sustainable dimensions - economic, social and environmental - by means of appropriate performance indicators and brings in itself the functional linkages among the criteria adopted in the evaluation practice, overtaking the weighting attributes to each one. The index achievable by the CI workflow is consequently balanced against the relative weight among the attributes. The development of CI facilitates the solution of the problems of ranking interventions on a territorial scale among different contexts evaluated from the point of view of sustainability. In fact, CI is effective in assessing balanced and unbalanced results across sustainable dimensions, taking care to monitor the different degrees of interaction among them. CI is a generalization of the best known and most widely used weighted average operators (GM, AM), but what distinguishes them as aggregation operators from weighted average operators is their usefulness in the presence of interacting elements. Limits of the proposed methodology could be found in the possible difficulty of immediately replicating the proposed method because of its intricate mathematical structuring.

However, the definition of an evaluation index with the CI method permits to take into account the actual social, economic and environmental imbalances of each territory/context examined. This leads to interesting and significant implications in terms of evaluation of sustainable performance, especially for the identification of political-urban realities to be given priority in terms of investments in order to effectively allocate financial resources among member countries of the same community (e.g. the European Community) and to support the sustainable development of countries with unbalanced realities, with a view to intergenerational equity [57]. Future research developments are aimed at making the IC method as operable as possible to those who need the realization of an evaluation index to be used in decision-making systems of interest, such as those aimed at the selection of investments for sustainable land development. Also, the CI methodological approach applied to different geographical contexts can be effective in fostering the improvement of territorial realities, by considering the existing socio-economic and environmental inequalities, and not only the main performance aspects.

4 Conclusions

In the design and monitoring of policy strategies aimed at increasing global sustainability, it is necessary that decision-makers are supported - at all stages - by tools, techniques and methodologies that enable them to carry out synthetic assessments as quickly as possible. It is also relevant that these tools could capture the complexity of available data and they are able to integrate in a single assessment the many aspects related to the assessment of sustainability, by involving characteristics of economic, social and environmental sustainability. The use of composite indices, based on the aggregation of analytical data, turns out - to date - to be very effective in supporting Public Administrations and politicians in the identification and selection of sustainable project solutions consistent with the objectives expressed in the 17 Sustainability Goals expressed in the 2030 Agenda [58, 59].

In this sense, the adoption of indices constitutes a relevant support for the Public Administrations in the planning of sustainable strategies, as they allow to adequately consider the multiple aspects of sustainability, as well as the effects generated by the intervention in the reference context. In fact, the proposed methodology is particularly effective in considering different degrees of positional interactions among pairs of dimensions related to sustainability. Specifically, CI allows to highlight the preferences of policy-makers and public agencies based on different sets of preferences, including a variety of levels of interaction among pairs of dimensions and different relative importance of the dimensions (considering the logic of the Shapley function). Moreover, the proposed methodology is able to determine the multiple positive interactions among sustainable dimensions. In fact, the definition of an evaluation index with the CI method permits to take into account the effective social, economic, and environmental unbalances 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.

In this perspective, further developments of the application of the proposed methodology to both the Italian and European contexts have already been planned, in order to fully analyze the interactions among the sustainability indicators and to obtain a representative measure of sustainability according to the factors of the urban contexts considered: for example, taking into account the current pandemic contingence, it could be possible to compare the effect of Covid-19 pandemic on the real estate market [60], or the sustainability of the same urban context before and after the Covid-19 pandemic. This will allow to carry out a constant monitoring of the conditions of sustainability of the considered urban contexts, by contributing to the achievement of shared sustainable objectives.

References

1. Fleurbaey, M.: Beyond the GDP: the quest for a measure of social welfare. J. Econ. Literat. **47**(4), 1029–1075 (2009)
2. Fleurbaey, M., Blanchet, D.: Beyond GDP: Measuring Welfare and Assessing Sustainability. Oxford University Press (2013)
3. Sen, A.: Commodities and capabilities. OUP Catalogue (1999)
4. Sen, A.: The Standard of Living: The Tanner Lectures. Cambridge University Press (1987)
5. Giovannini, E., Hall, J., D'ercole, M.M.: Measuring well-being and societal progress. In: Conference Beyond GDP-Measuring progress. true wealth, and the well-being of nations, pp. 19–20. European Parliament, Brussels (2007)
6. Istanbul Declaration. https://ec.europa.eu/environment/beyond_gdp/download/oecd_istanbul_declaration.pdf. Accessed 12 Dec 2021
7. Beyond GDP. https://ec.europa.eu/environment/beyond_gdp/index_en.html. Accessed 12 Dec 2021
8. Atkinson, A.B., Marlier, E., Wolff, P.: Beyond GDP, measuring well-being and EU-SILC. Income Living Cond. Europe **387** (2010)
9. European Commission: Non solo Pil. Misurare il progresso in un mondo in cambiamento. Comunicazione della Commissione al Consiglio e al Parlamento europeo. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52009DC043. Accessed 27 Dec 2021
10. Isabelle, C.: Beyond GDP, Measuring progress, true wealth, and the well-being of nations: Conference Proceedings. n/a (2009)
11. Ness, B., Urbel-Piirsalu, E., Anderberg, S., Olsson, L.: Categorizing tools for sustainability assessment. Ecol. Econ. **60**(3), 498–508 (2007)
12. UNDP: Human Development Report 2010: The Real Wealth of Nations - Pathways to Human Development. http://hdr.undp.org/en/content/human-development-report-2010. Accessed 27 Dec 2021
13. Wendling, Z.A., Emerson, J.W., de Sherbinin, A., Esty, D.C.: Environmental Performance Index. Yale Center for Environmental Law & Policy (2020)
14. Dobrovolskienė, N., Tvaronavičienė, M., Tamošiūnienė, R.: Tackling projects on sustainability: a Lithuanian case study. Entrep. Sustain. Issues (4.4), 477–488 (2017)
15. Attardi, R., Cerreta, M., Sannicandro, V., Torre, C.M.: Non-compensatory composite indicators for the evaluation of urban planning policy: the Land-Use Policy Efficiency Index (LUPEI). Eur. J. Oper. Res. **264**(2), 491–507 (2018)
16. Alkire, S., Santos, M.A.: Measuring acute poverty in the developing world: robustness and scope of the multidimensional poverty index. World Dev. **59**, 251–274 (2014)

17. Decancq, K., Lugo, M.A.: Weights in multidimensional indices of well-being: an overview. Economet. Rev. **32**(1), 7–34 (2013)
18. Pinar, M., Stengos, T., Topaloglou, N.: Measuring human development: a stochastic dominance approach. J. Econ. Growth **18**(1), 69–108 (2013)
19. Pinar, M., Cruciani, C., Giove, S., Sostero, M.: Constructing the FEEM sustainability index: a Choquet integral application. Ecol. Ind. **39**, 189–202 (2014)
20. Ravallion, M.: Troubling tradeoffs in the human development index. J. Dev. Econ. **99**(2), 201–209 (2012)
21. Chakravarty, S.R.: A generalized human development index. Rev. Dev. Econ. **7**(1), 99–114 (2003)
22. Chakravarty, S.R.: A reconsideration of the tradeoffs in the new human development index. J. Econ. Inequal. **9**(3), 471–474 (2011)
23. Pinar, M.: Multidimensional well-being and inequality across the European regions with alternative interactions between the well-being dimensions. Soc. Indic. Res. **144**(1), 31–72 (2019)
24. Athanassoglou, S.: Multidimensional welfare rankings underweight imprecision: a social choice perspective. Soc. Choice Welfare **44**(4), 719–744 (2015)
25. Cherchye, L., Ooghe, E., van Puyenbroeck, T.: Robust human development rankings. J. Econ. Inequal. **6**(4), 287–321 (2008)
26. Foster, J.E., McGillivray, M., Seth, S.: Composite Indices: rank robustness statistical association, and redundancy. Economet. Rev. **32**(1), 35–56 (2013)
27. Pinar, M.: Choquet-integral aggregation method to aggregate social indicators to account for interactions: an application to the human development index. Soc. Indic. Res. **159**(1), 1–53 (2021). https://doi.org/10.1007/s11205-021-02726-3
28. Pinar, M., Stengos, T., Topaloglou, N.: On the construction of a feasible range of multidimensional poverty under benchmark weight uncertainty. Eur. J. Oper. Res. **281**(2), 415–427 (2020)
29. Rogge, N.: On aggregating benefit of the doubt composite indicators. Eur. J. Oper. Res. **264**(1), 364–369 (2018)
30. Choquet, G.: Theory of capacities. Ann. De L'institut Fourier **5**, 131–295 (1953)
31. Murofushi, T., Sugeno, M.: An interpretation of fuzzy measures and the Choquet integral as an integral with respect to a fuzzy measure. Fuzzy Sets Syst. **29**(2), 201–227 (1989)
32. Meng, F., Zhang, Q., Cheng, H.: Approaches to multiple-criteria group decision making based on interval-valued intuitionistic fuzzy Choquet integral with respect to the generalized λ-Shapley index. Knowl. Based Syst. **37**, 237–249 (2003)
33. Labreuche, C., Grabisch, M.: The Choquet integral for the aggregation of interval scales in multicriteria decision making. Fuzzy Sets Syst. **137**(1), 11–26 (2003)
34. Mazziotta, M., Pareto, A.: Methods for constructing non-compensatory composite indices: a comparative study. Forum Soc. Econ. **45**, 213–229 (2016)
35. Grabisch, M.; Marichal, J.L.; Mesiar, R.; Pap, E.: Aggregation Functions. Cambridge University Press (2009)
36. Grabisch, M., Labreuche, C.: A decade of application of the Choquet and Sugeno integrals in multicriteria decision aid. Ann. Oper. Res. **175**(1), 247–286 (2010)
37. Meyer, P., Ponthière, G.: Eliciting preferences on multi-attribute societies with a Choquet Integral. Comput. Econ. **37**(2), 133–168 (2011)
38. 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. **245**(1), 427–456 (2016)
39. Oppio, A., Bottero, M., Arcidiacono, A.: Assessing urban quality: a proposal for a MCDA evaluation framework. Ann. Oper. Res. , 1–18 (2018). https://doi.org/10.1007/s10479-017-2738-2

40. Gálvez Ruiz, D., Diaz Cuevas, P., Braçe, O., Garrido-Cumbrera, M.: Developing an index to measure sub-municipal level urban sprawl. Soc. Indic. Res. **140**, 929–952 (2018)
41. Carraro, C., Campagnolo, L., Eboli, F., Lanzi, E.; Parrado, R., Portale, E.: Quantifying sustainability: a new approach and world ranking. FEEM **94** (2013)
42. 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. **224**(3), 603–613 (2013)
43. Bertin, G., Carrino, L., Giove, S.: The Italian regional well-being in a multi-expert non-additive perspective. Soc. Indic. Res. **135**, 15–51 (2018)
44. 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. **245**(3), 837–850 (2015)
45. 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. **271**(1), 120–140 (2018)
46. 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. **250**(3), 884–901 (2016)
47. Campagnolo, L., Carraro, C., Eboli, F., Farnia, L., Parrado, R., Pierfederici, R.: The Ex-Ante evaluation of achieving sustainable development goals. Soc. Indic. Res. **36**, 73–116 (2016)
48. 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. **186**(2), 766–785 (2008)
49. Marichal, J.L., Roubens, M.: Determination of weights of interacting criteria from a reference set. Eur. J. Oper. Res. **124**(3), 641–650 (2000)
50. Shapley, L.S.: A value for n-person games. In: Kuhn, H.W.; Tucker A.W. (eds.) Contributions to the Theory of Games. Princeton University Press (1953)
51. Grabisch, M.: Fuzzy integral in multicriteria decision making. Fuzzy Sets Syst. **69**(3), 279–298 (1995)
52. Grabisch, M.: The application of fuzzy integrals in multicriteria decision making. Eur. J. Oper. Res. **89**(3), 445–456 (1996)
53. Meyer, P., Roubens, M.: On the use of the Choquet integral with fuzzy numbers in multiple criteria decision support. Fuzzy Sets Syst. **157**(7), 927–938 (2006)
54. Marichal, J.L.: Tolerant or intolerant character of interacting criteria in aggregation by the Choquet integral. Eur. J. Oper. Res. **155**(3), 771–791 (2004)
55. Murofushi, T., Soneda, S.: Techniques for reading fuzzy measures (iii): Interaction index. In: 9th Fuzzy System Symposium, pp. 693–696, Japan (1993)
56. Grabisch, M.: K-order additive discrete fuzzy measures and their representation. Fuzzy Sets Syst. **92**(2), 167–189 (1997)
57. Tajani, F., Guarini, M.R., Sica, F., Ranieri, R., Anelli, D.: Multi-criteria analysis and sustainable accounting. defining indices of sustainability under Choquet's integral. Sustainability **14**(5), 2782 (2022)
58. Anelli, D., Sica, F.: The financial feasibility analysis of urban transformation projects: an application of a quick assessment model. In: Bevilacqua, C., Calabrò, F., Della Spina, L. (eds.) International Symposium: New Metropolitan Perspectives, SIST, vol. 178, pp. 462–474, Springer, Cham (2020). https://doi.org/10.1007/978-3-030-48279-4_44

59. 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: International Conference on Computational Science and Its Applications, LNTCS, vol. 12954, pp. 210–225, Springer, Cham (2021). https://doi.org/10.1007/978-3-030-86979-3_16
60. Tajani, F., Liddo, F.D., Guarini, M.R., Ranieri, R., Anelli, D.: An assessment methodology for the evaluation of the impacts of the COVID-19 pandemic on the italian housing market demand. Buildings **11**(12), 592 (2021)