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Constructing the FEEM Sustainability Index: A Choquet-Integral Application

By **Caterina Cruciani**, Fondazione Eni Enrico Mattei and Ca' Foscari University of Venice, Italy

Silvio Giove, Fondazione Eni Enrico Mattei and Ca' Foscari University of Venice, Italy

Mehmet Pinar, Fondazione Eni Enrico Mattei, Italy

Matteo Sostero, Fondazione Eni Enrico Mattei and Ca' Foscari University of Venice, Italy

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By Caterina Cruciani, Fondazione Eni Enrico Mattei and Ca' Foscari
University of Venice, Italy

Silvio Giove, Fondazione Eni Enrico Mattei and Ca' Foscari University of
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Mehmet Pinar, Fondazione Eni Enrico Mattei, Italy

Matteo Sostero, Fondazione Eni Enrico Mattei and Ca' Foscari
University of Venice, Italy

Summary

This paper presents an application of a multi-attribute aggregation methodology to the construction of a sustainability index. Sustainability is a multi-faceted issue, in which synergies or conflicts may arise among the different components, thus making it a complex concept to which multi attribute methods can be applied. This paper addresses the development of the FEEM Sustainability Index (FEEM SI), a composite index including 19 different indicators grouped in the three classical pillars of sustainability –economic, social and environmental. We present the relevance of multi-attribute aggregation methodologies when dealing with such complex concepts and provide an aggregation methodology used for this case study, the Choquet-integral aggregation. In particular, since this methodology requires the assignment of weights on indicators and their coalitions, an ad hoc questionnaire is implemented to assess the importance of sustainability indicators through expert elicitation. After computing consensus weights for the Choquet-integral aggregation procedure the overall sustainability index, the FEEM SI is calculated. This paper also conducts robustness analysis and discusses the main implications of the aggregation methodology used.

Keywords: Sustainability Indices, Composite Indicators, Choquet Integral, Multiattribute Value Theory

JEL Classification: C43, C44, Q01, Q56

Address for correspondence:

Mehmet Pinar
Fondazione Eni Enrico Mattei
Isola di San Giorgio Maggiore, 8
30124 Venice
Italy
Email: mehmet.pinar@feem.it

Constructing the FEEM Sustainability Index: a Choquet-integral application

Caterina Cruciani^{*°}, *Silvio Giove*^{*°}, *Mehmet Pinar*^{*}, *Matteo Sostero*^{*°}

^{*}Fondazione Eni Enrico Mattei, [°]Ca' Foscari University of Venice

Abstract

This paper presents an application of a multi-attribute aggregation methodology to the construction of a sustainability index. Sustainability is a multi-faceted issue, in which synergies or conflicts may arise among the different components, thus making it a complex concept to which multi-attribute methods can be applied. This paper addresses the development of the FEEM Sustainability Index (FEEM SI), a composite index including 19 different indicators grouped in the three classical pillars of sustainability – economic, social and environmental. We present the relevance of multi-attribute aggregation methodologies when dealing with such complex concepts and provide an aggregation methodology used for this case study, the Choquet-integral aggregation. In particular, since this methodology requires the assignment of weights on indicators and their coalitions, an ad-hoc questionnaire is implemented to assess the importance of sustainability indicators through expert elicitation. After computing consensus weights for the Choquet-integral aggregation procedure the overall sustainability index, the FEEM SI is calculated. This paper also conducts robustness analysis and discusses the main implications of the aggregation methodology used.

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Address for correspondence: Mehmet Pinar

Fondazione Eni Enrico Mattei, Isola di San Giorgio Maggiore, 8, 30124 Venice, Italy

Email: mehmet.pinar@feem.it

1. Introduction

Sustainability is somewhat an elusive concept: although its main message is widely understood, it is quite hard to come by two identical descriptions of it, when it comes to spelling out its different components. The most used definition of sustainable development is given in the Brundtland report as “Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED, 1987). Achieving a sustainable development has been one of the major concerns of modern societies, which have long been interested in understanding and governing the multi-faceted issue of development, thus making a comprehensive assessment of sustainability crucial to measure progress, identify areas to be addressed and evaluate the outcome of implemented policies. The need to find ways to measure sustainability translated into a plethora of approaches and sustainability indicators that have been differently aggregated in different ways to obtain composite indices. For a methodological review on the sustainability, see Bossell (1999), OECD JRC (2008), and Singh et al. (2009); and for list of sustainability indicators refer to the EU core set of indicators (EEA, 2005), and the UN Commission on Sustainable Development (2005).

This paper focuses on the methodological issues regarding the construction of a composite index of sustainability, which is an area that has been gaining interest in empirical literature due to its high policy potential. In fact, a composite index allows for a quick assessment of sustainability performance across different countries and at different times. Moreover, sustainability indices conveys a straightforward message to stakeholders and policy makers, and also are able to highlight best practices and weaknesses of sustainability strategies (Ness et al. 2007).

Such a sustainability index needs to be constructed very carefully using a procedure as transparent as possible, in order to gain trust in the policy arena. Moreover, sustainability is characterized by many different aspect that are somewhat linked one to the other, which rules out the possibility of using simple aggregation techniques, which risk to lose too much information regarding interactions across indicators.

The policy potential of an aggregate measure coupled with the complexities behind the relations across the indicators that define sustainability make it an area to employ a non-linear aggregation methodology, which is able to target specifically the interactions across the different components of sustainable development.

The contribution of this paper is twofold. The main contribution is to construct a composite sustainability index by applying a non-linear aggregation methodology (i.e., the Choquet integral) which accounts for the interactions among sustainability indicators. Singh et al. (2009) summarizes forty one sustainability indicators used in the literature and majority of those indices are either aggregated through equal weight assignment (e.g., Environmental Sustainability Index, Human Development Index, Sustainability Performance Index, etc.) or weights given by experts (e.g., Index of Environmental Friendliness) to each sustainability indicator. However, none of those indices allow to capture the inter-relations among different sustainability indicators. In other words, those aggregation methodologies do not account for synergies or redundancies when indicators are aggregated (e.g., see Panayotou (1993), Grossman and Krueger (1993) and Selden and Song (1994) for discussion on the relationship between economic growth and environmental quality). In the construction of the FEEM Sustainability Index (FEEM SI hereafter), we are able to address specifically the inter-relations across indicators, thus overcoming the limitations of other aggregation methodologies.

Another contribution of the current paper is the expert elicitation and the derivation of weights for each sustainability indicator and their coalitions among each other. An ad-hoc questionnaire is implemented to assess the importance of sustainability indicators through expert elicitation. As the Brundtland report suggests, sustainable development “meets the needs of the present without compromising the ability of future generations”, therefore, the relative importance of different indicators has to be evaluated through expert elicitation . However, the aggregated index strongly depends on the *subjective relative importance* of coalitions between different sustainability indicators, which may be different for each expert. Therefore, we derive a consensus measures on sustainability indicators from many expert elicitations by using a metric distance (i.e., if the evaluation of an expert is in agreement with other experts, then this expert’s valuation gets higher weight. Thus, if an expert’s valuation of sustainability indicators is extremely different than other experts, then relatively lower weight is assigned to this type of expert valuation). After obtaining the consensus measures, we employ Choquet integral to aggregate the normalized sustainability indicators to obtain the final FEEM SI outcome for the countries (macro-regions) in our analysis.

The remainder of the paper is as follows. In section 2, we review the theoretical contributions of the Choquet integral as an aggregation methodology in the sustainability context pointing out useful properties and features. In section 3, we provide the stages of aggregation framework for the FEEM SI. We first introduce the sustainability indicators considered in this study and where those indicators are located in the aggregation tree. We offer the construction of an ad-hoc questionnaire to assess the importance of sustainability indicators through expert elicitation. We provide the derivation of the representative weights of sustainability indicators and offer the main characteristics of expert elicitations. In section 4, we provide the FEEM SI scores for countries and macro-regions. We also conduct comparisons of sustainability outcomes between the Choquet integral and alternative aggregation operators. Furthermore, we obtain FEEM SI scores by simulating different expert elicitations from the real expert elicitations and use those in the aggregation procedure to analyze whether the results obtained through representative measures are robust. Finally, section 5 concludes and discusses the possible extension of the current study. Detailed mathematical formulations used for aggregation are gathered in an Appendix.

2. Multi attribute aggregation

Sustainability evaluation is a multi-attribute problem, since it is characterized by many different components that interact with each other. In the specialized literature several approaches exist to deal with multi attribute problems, each characterised by specific mathematical properties, which have very different implications. In this section, we briefly review possible aggregation options and provide elements to understand why sustainability cannot be fully addressed by some of them. Vincke (1999) classifies into three categories the main approaches:

- Multi Attribute Value Theory (MAVT);
- outranking approaches;
- interactive approaches.

Among the three, MAVT-based techniques have been more extensively used in multi attribute problems given the great diversity of methods fall under this broad category of approaches. In MAVT, starting from the criteria evaluation a single aggregated score has to be computed, expressed in a finite scale as $[0,1]$ with the usual meaning: 0 means “very bad”, 1 means “very good”. The problem can also be structured as a hierarchal tree, and in this case the criteria are the leaves of the tree, , and the root of the tree is the sustainability evaluation, as is the case for the analysis carried out in this paper. In general, the MAVT methods use an aggregation algorithm to compute a score for each alternative

(Klement et al., 2000). A MAVT method is characterized by two subsequent phases; in the first one all the criteria are normalized in a common scale, usually the $[0,1]$ scale, in order to allow direct comparisons. In the second phase, the normalized values are aggregated using a suitable function, i.e., an Aggregation Operator (AO), an idempotent and monotonic multidimensional function which maps the n -dimensional $[0,1]$ side hyper-cube in the closed $[0,1]$ interval. In particular, monotonicity is a strong requirement implying that, *ceteris paribus*, “more” is preferred to “less”. In the case of a tree structure, the aggregation phase will be (bottom up) calculated for each node, starting from the lowest level (the *leaves* of the tree) up to the root (in our case, the sustainability evaluation). For a complete description of AO properties, see Klement et al. (2000).

A broadly used MAVT-based aggregation technique is the **Weighted Average (WA)**, which relies on the (simple) arithmetic weighted average of the (normalized) indicator values. The most common case is the one where the weights are the same for all the indicators, the Equally Weighted Average (EWA) method. Despite the fact that this method is simple and intuitive, the linearity of the aggregation function implies constant substitutability among the criteria which is not a very reasonable assumption, given the nature of the sustainability indicators and could lead to double counting. Nevertheless, it also implies recognising the lack of empirical scientific proofs on the relative importance of different sustainability indicators (Nardo et al. 2005) and is considered the most transparent way of producing aggregate indices (Environmental Sustainability Index, ESI, 2005). In real world applications, WA may be applied with particular care only to the case where no interactions exist among the criteria -an unlikely and quite rare situation. In fact, the substitutability very often fails to be satisfied, which means that the compensative assumption (technically, the Preferential Independent axiom, see Marichal and Roubens, 2000) is unsatisfied; therefore, WA cannot be implemented for the aggregation procedure.¹ For the cases where WA cannot be used, many other methods have been proposed in the MAVT context, such as the multiplicative approach, the compensation operator (Von Altrock, 1995) or the Ordered Weighted Averaging (**OWA**) operator (Yager, 1993).

As discussed above, specific properties of an aggregation operator are required to aggregate the sustainability indicators. In particular, aggregation operators should be easily parameterized and tuned by the decision maker, and not necessarily implying compensability, while conversely they need to be mathematically well founded and characterized.

Capacities (non-additive measures, fuzzy measures) can be a solution, as they satisfy those formal requirements. In fact, a non-additive measure (NAM) operator satisfies many theoretical requirements, and, at the same time, it is sufficiently general to cover a lot of preference structures of the Decision Maker (**DM**). Many types of interactions can be modelled in this way. Any behaviour of the decision maker can also be introduced such as the *pessimistic* or *optimistic* behaviour, which indicate respectively that the satisfaction degree is high only if *all* the criteria are satisfied (corresponding to the logical conjunction operator AND), or if *at least one* of them is high (corresponding to the logical disjunction operator OR). Note that both cases cannot be implemented by **WA**. The NAM operator is based on the observation that the linearity implicitly assumed in **WA** can be violated, that is, the “weight” of a coalition of sub-criteria can be greater or less than the sum of the weights of each of the sub-criterion belonging to the coalition itself. Thus, the main idea consists into assigning a weight to *every possible* subset of the criteria which refer to the considered node in the tree. Such NAM methods are nothing but an extension of the weighted average, in which instead of assigning a weight to each indicator, we assign a weight to each possible coalition of them. Then the algorithm simply aggregates every

¹ The compensative assumption is rarely tested in practical applications, but missing this check can induce a strong distortion in the decisional process.

coalition computing the weighted average of each subset. Anywise, the computation becomes exponentially more complex as the number of parameter increases. In fact, if n is the number of the criteria, a **NAM** requires the specification of 2^n parameters, i.e. the number of all the subsets of the n criteria, while the **WA** approach requires n parameters only.² Nevertheless, this problem can be overcome by limiting the number of indicators in each node to a small number.

Among the possible NAM, the Choquet integral satisfies many properties, which make it an effective tool in the analysis of multi attribute problems such as sustainability. Varying the value of the measures, the Choquet integral can be reduced to min or max operators, or ordered weighted average, or a mixture of them. Thus, according to the features of the DM preferences we can tune the measure values and obtain several interesting sub-cases. If for every coalition the weight (or the *importance*) of each coalition is formed by the sum of the weights of each sub-set of its criteria forming a partition, we obtain the **WA**. Conversely, if for a coalition its weight is *inferior* to such a sum, a *redundant* interaction exists among the included criteria, while if it is *greater* than the sum, a *synergic* interaction exists. A formal description of the Choquet integral, together with some properties and an alternative representation (the Möbius transform) is described in Appendix A.

3. Conceptualizing sustainability: the FEEM Sustainability Index

In this section we introduce the aggregation methodology developed for the FEEM SI, an aggregate sustainability index characterized by 19 indicators belonging to the three pillars of sustainability (i.e., economic, social and environmental). The indicators are constructed within a recursive-dynamic general equilibrium model ICES-SI (Carraro et al., 2012)³, which allows producing future projections of all indicators in the time frame 2011-2020 that can be used in comparative static policy analysis. The indicators are then normalized using a policy-oriented benchmarking technique developed ad hoc for the FEEM SI before proceeding to the aggregation stage.⁴ For further details on the construction of the FEEM SI, see Carraro et al. (2012).

The aggregation methodology prepared for the FEEM SI builds on the capacities of the multi attribute aggregation methodology, partially following Despic and Simonovic (2000), who provides a three-step procedure to deal with the evaluation of complex concepts that are naturally composed of numerous sub-elements.⁵ Their contribution is to reduce the complexity behind the analysis of a system by proceeding with a “hierarchical analysis of its less complex components” (Despic and Simonovic, 2000). Sustainability certainly qualifies as a complex issue, thus making it a viable case to apply a methodology along the same lines as Despic and Simonovic (2000). The methodology used for the FEEM SI differs in a number of respects from the original work of Despic and Simonovic (2000), but retains their main idea and makes use of a hierarchical analysis.

The **decomposition** of sustainability into a set of indicators is necessary to construct a decision tree representing this hierarchical decomposition was carried out by the research team of the FEEM SI. This index deals with global

² To be exact, there are $2^n - 2$ required parameters since the *border* conditions are already predetermined in which the empty set is null and the universal set is one.

³ ICES-SI model is an extended version of ICES model (see Eboli et al. 2010). See also Carraro et al. (2012), Annex II for the detailed construction of the ICES-SI model.

⁴ Each indicator is converted into a common scale between 0 and 1 which allows a full comparison among indicators. See FEEM Sustainability Index Methodological Report 2011, Section 3 for the normalization procedure and detailed indicator benchmarks.

⁵ The three steps proposed by Despic and Simonovic (2000) are decomposition of the system, evaluation of the lower components and aggregation.

sustainability, thus the subjects of this sustainability analysis are states and macro regions. Differently from other applications of multi-attribute methods for aggregation in the realm of environmental issues, the relevant stakeholders are not involved in the selection of the indicators that form the FEEM SI, both for the complexity of achieving a balanced and representative sample and also for the vast amount of related literature on the subject, which already provides numerous suggestions at a much lower organizational cost. The definition of the components of the FEEM SI is thus defined on the basis of a thorough literature review including the work of international institutions involved in sustainability analysis.⁶ The indicators selected for the FEEM SI have been organised into a decision tree, in which partial aggregation take place at different levels, leading to the hierarchical decomposition of Figure 1.

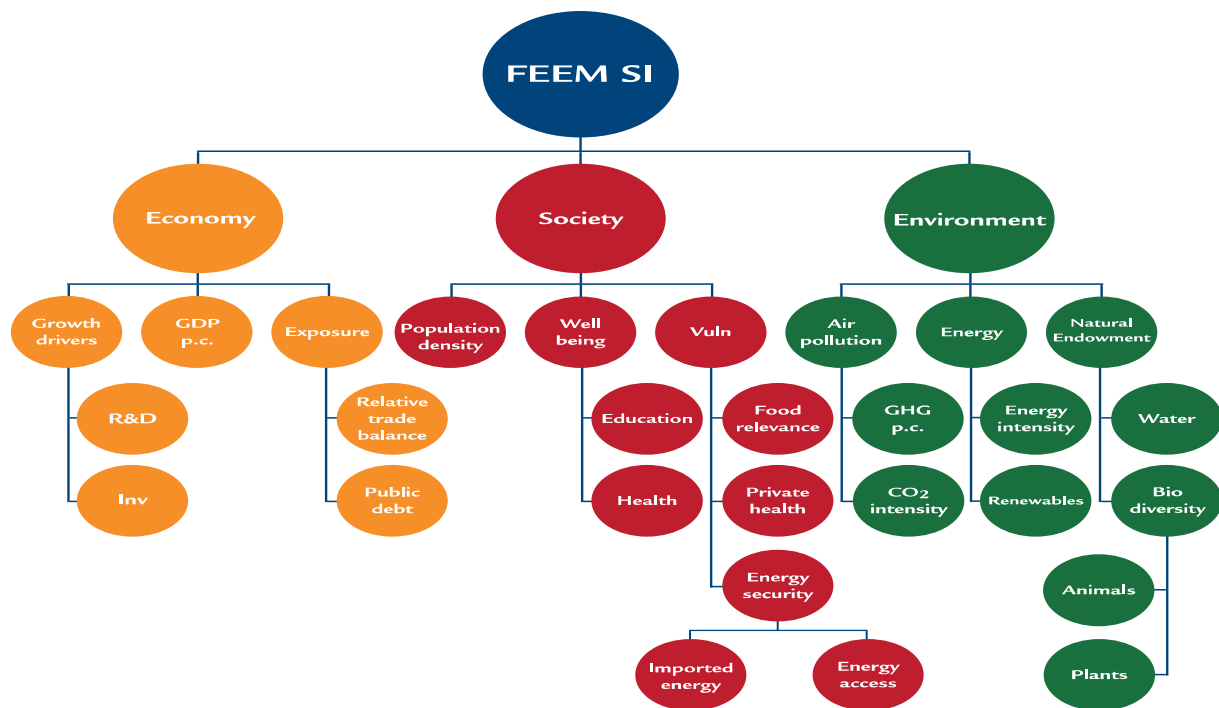


Figure 1: FEEM SI Aggregation tree

The decision tree should be read from bottom (leaves) to top (final node) and is characterised by three successive decomposition levels. The tree respects the three main pillar structure which is quite standard in most sustainability studies (see e.g., The United Nations Commission for Sustainable Development (UN CSD); Global Reporting Initiative (GRI) framework; Krajnc and Glavic, 2005), with the final node producing the aggregate index.⁷

The second stage of the procedure requires the **evaluation** of the subcomponents at each one of the three levels of the decomposition, starting from the bottom node of the aggregation tree. Differently from other procedures, where a relative weight is defined for each indicator with respect to the others, the decision tree also requires to attribute weights to the coalitions of indicators at each node.

The procedure is based on the definition of a fuzzy measure, but instead of evaluating all the possible combinations among all possible levels of the indicators at each node, the procedure inspired from Despic and Simonovic (2000) allow to focus on some specific combinations of given levels of the indicators. Indicators can take in theory a wide range of

6 See FEEM Sustainability Index Methodological Report 2011, section 1.2 for detailed indicator selection process, their descriptions and the affiliation area of each indicator to each sustainable development dimension.

7 Both the UN CSD analyzes four main dimensions in their framework including the institutional (governance) dimension and future development of the FEEM SI is to include the governance dimension into the analysis of sustainability assessment.

values, but in this procedure only two extreme qualitative values were identified and labelled “best” and “worst”. All the indicators of the FEEM SI are quantitative in nature, due to the features of the modelling environment in which they have been developed, yet the aggregation methodology has been constructed using “qualitative” evaluations in order to make the procedure more comprehensible.

Contrary to what Despic and Simonovic (2000) suggests, no specific numerical definitions have been given for these two levels for each indicator; given the broad scope of the exercise –global sustainability- and the relevance of including in the stakeholder group used to evaluate the questionnaire a wide variety of backgrounds, a more neutral setting has been preferred. As a later section will detail, experts in the questionnaire have been asked to make reference to their own ideal “best” and “worst” for each indicator. Moreover, avoiding numerical evaluations of best and worst levels rules out bias deriving from respondents disagreeing with the judgement given.

The third and final step of the procedure is to find an appropriate **aggregation** algorithm to the problem at hand. In this case study, the construction of an aggregate sustainability index requires selecting a procedure that allows for different relations across the different indicators. For instance, a sustainable policy requires economic development not to be obtained at the price of an increase in environmental pollution, while a better healthcare policy may have spill over effects on other welfare programmes. In order to account for all these aspects any aggregation methodology that is additive in nature cannot be chosen: a good performance in some indicators cannot compensate for a poor one in others. Thus, a methodology that allows for **non-compensative aggregation** has to be chosen, in which the different relation across indicator can be carefully represented. Looking at other broader categories of aggregation algorithms shows that a low level of compensation cannot be achieved by **EWA**, but neither by **WA** with different values of the weights.

Moreover, in the case of the FEEM SI a further requirement has been set for the analysis, namely the respect of a monotonicity criterion. This principle implies that the importance of a coalition of criteria (components) cannot be less than the maximum of the weight of each sub-coalition included in it. Thus, adding a component to another can never be detrimental to the overall evaluation, but can at most produce no variation in the weight given to the initial component.

Among the different aggregation algorithms introduced in the previous section the multi-linear aggregation operator, variation of the Choquet integral in which the T-norm product is used instead of the T-norm minimum, has been chosen for the aggregation process of the FEEM SI.

3.1 Features of the questionnaire

In order to obtain the weights that are necessary to compute the fuzzy measure for the aggregation, a simple paper-based questionnaire has been prepared, which includes a decision matrix for each one of the 12 decomposition nodes of the aggregation tree. The questionnaire can be thought of as a list of the possible scenarios with two defined qualitative levels of the indicators, i.e. all the combinations of BEST and WORST values. If n is the number of sub-components of the considered node, the decision matrix will then have 2^n rows, thus requiring the same number of evaluations by the respondent.

The computation of the aggregated index strongly depends on the *subjective relative importance* of a coalition with respect to another one, reflecting the positive or negative interaction among the criteria (Grabisch et al., 2003). If the

measure of a coalition is greater than the sum of its components, there is a synergic interaction, if inferior, a redundant one, if equal, no interaction at all, as in the WA linear approach. The Choquet integral can be directly calculated from the values of the criteria and the measure values. It is an averaging operator see (Klement et al., 2000) and thus is bounded from above by the MAX and from below by the MIN operator.

The values of the measure are obtained from the elaboration of the questionnaire developed by Despic and Simonovic (2000). The questionnaire is a list of some possible scenarios, i.e. all the combinations of BEST and WORST values. Again 2^n is the number of possible questions, and the respondent needs to fulfil the last column with a number in between 0 (worst case) and 100 (best case), respecting the monotonicity constraints, i.e., the measure of a set (coalition of criteria) cannot be less than the measures of the subset forming a partition of it.

Economic	Social	Environmental	Weights
Worst	Worst	Worst	0
Best	Worst	Worst	20
Worst	Best	Worst	50
Worst	Worst	Best	30
Best	Best	Worst	$X \geq 50$
Best	Worst	Best	$X \geq 30$
Worst	Best	Best	$X \geq 50$
Best	Best	Best	100

Figure 2: Construction of Indicator-Coalition Matrix

The respondents have to provide a numerical evaluation for each row of the decision matrix, which is provided for all 12 decomposition nodes, choosing a value between 0 and 100 for each row, except for the first and the last (where indicators are respectively all “worst” and all “best”) which are given 0 and 100 by default. Moreover, the weights given at each row of every matrix need to respect the monotonicity criterion introduced in the previous section. This implies that, if a combination where only one indicator is “best” is given a certain weight x , all combinations including that indicator in the “best” case should be given a weight at least equal to x , as the Figure 2 illustrates an example.

Once the questionnaire is complete, the numerical evaluations are imputed to a software that computes the fuzzy measures and combines them with the indicator value to provide sustainability country rankings for each year of the analysis.

3.2 Decision maker behaviour

One important feature of this non-additive methodology is that in principle it allows to be extremely flexible in the definition of the degree of compensability across indicators. Although we rule out negative synergies (thanks to the introduction of a monotonicity criterion), many degrees of positive ones are possible. The level of compensation implicit in the weights assigned by the experts can be quantified by means of two complementary indices, the **ANDNESS** and **ORNESS** indices, often referred to as characterising an optimistic and a pessimistic decision maker. The sum of these indices is always 1, with each of them being given a score between 0 and 1. An ANDNESS degree close to 1 indicates that the decision maker tends to be *non-compensative*, meaning that he/she would not accept that a good performance in one sub-criteria compensates for a negative one in another. On the contrary, an ORNESS degree close to 1 indicates that

the decision maker is satisfied even if only one sub-criterion is at “best” level. Given the nature of the problem at hand, it seems more likely that decision makers evaluating the hierarchical structure of the FEEM SI tree should be more inclined towards andness, as sustainability implicitly requires a balanced development across its different components. Sustainability is a complex issue, fraught with synergies and tradeoffs that often make good policy-making difficult. The profile of preference for compensability will fundamentally affect how weights are assigned to the different coalitions of indicators, thus becoming a very important aspect of this analysis. Besides looking at the compensability profile of each decision maker, it is also necessary to investigate ways to aggregate different opinions into a single measure that represents the initial individual position to the highest possible degree.

Moreover, interaction among criteria (i.e., interaction indices) is also an important characteristic of Choquet integral that adds valuable information to the sustainability concept, is considered in the current analysis. ANDNESS and ORNESS indices offer whether a decision maker’s characteristic is pessimistic or optimistic at a given node level however, one can analyze the interaction between two indicators at a given node. Suppose that the two indicators, i and j , are competitive (i.e. substitute) to each other, then the marginal contribution of indicator i to every combination of criteria that contains indicator j should be strictly less than the marginal contribution of i to the same coalition when j is excluded (i.e. negative interaction index for the indicators i and j). Reverse is true for the case when indicators i and j are complementary (i.e., positive interaction index for the indicators i and j). The interaction index lays between -1 and 1 , representing perfectly competitive (i.e. substitute) and perfectly complementary behaviour respectively. Given that, as suggested, the FEEM SI tree should be more inclined towards andness, one should also expect decision makers to have more complementary-oriented behaviour among the indicators. For example, a country having good economic AND environmental conditions should be evaluated more in sustainability terms than a country having only one indicators at the best level.

The next section will present the questionnaire used to assess the sustainability concept; in particular, we asked participants to evaluate sustainability indicators at each node independently, thus enabling us to analyze both how sustainability is evaluated by the respondents and whether they evaluate this concept relying towards more ANDNESS-oriented and positive interaction among indicators or not. Detailed mathematical derivation of the ANDNESS and interaction indices are offered in Appendix A.

3.2.1 Pilot study – Evaluation of sustainability

The FEEM SI 2011 derives all the weights (measures) starting from a survey of Experts evaluations, implemented using QUALTRICS software.⁸ Therefore, measures are the result of a careful reconstruction of individual preferences using a specifically-built questionnaire. In the questionnaire, Experts express their valuation for each indicator and their coalitions for each node separately. Figure 2 offers an example of the questionnaire in which Experts are asked to express their valuation on all possible combinations of the main three pillars (economic, social and environmental pillars) of the FEEM SI node. Similarly, the indicator-coalition matrices are offered to Experts at every node of FEEM SI tree, where all possible coalitions among indicators at that node are allowed. Experts of different backgrounds and affiliations completed the web-based questionnaire and were asked to come up with only one set of agreed numerical

⁸ Qualtrics is a private research software which enables one to build web-base surveys which is easy to distribute and allow world wide participation. Qualtrics software, furthermore, allows one to set questionnaires that are study specific which can be supported with exemplary questionnaires shown either in video and/or graphic illustrations. Once the questionnaire completed, it can be imported to Microsoft Excel file and/or statistical software programming SPSS. For further details of possible implications, please refer to <http://www.qualtrics.com/>

evaluations for all possible coalitions at each sub-node. In the current analysis, out of the total questionnaires completed, 20 of them satisfy the monotonicity axiom.⁹ An example of the questionnaire for the final node of FEEM SI decision tree is given in Appendix Table A.1.

3.3 Representative Decision Maker

Naturally, each respondent involved in the analysis has a valuation and attitude towards sustainability indicators at the different nodes. Thus, in order to derive ‘representative’ weights to assign to for each sustainability indicator and their coalitions at each node, a consensus measure among respondents has been considered. This measure is computed using the metric distance measure, which assigns higher weights to valuations in agreement (i.e. having lower distance measure) one with the other. However, if a respondent’s valuation of sustainability indicators is extremely different from other valuations (i.e. having a higher distance measure), then a relatively lower weight is assigned to this type of respondent. By doing so, a “consensus” weight for each sustainability indicator and their coalitions at every node of FEEM SI is obtained. A detailed derivation of representative decision maker from many respondents is given in Appendix A.¹⁰

Characteristics of the Decision Makers

In this section, we present the characteristics of the representative decision maker through the description of the ANDNESS and interaction indices for all sub-nodes of the FEEM SI decision tree. These indices will shed a light on the how “consensus” Decision Maker evaluate the sustainability indicators at each sub-node. In particular, one can assess whether the representative Decision Maker follows a more non-compensative behaviour at a given sub-node (i.e. having and ANDNESS index greater than 0.5) and if so, among which indicators there is a complementary (competitive) behaviour. Obviously, for the case of sub-nodes that have only two indicators, both ANDNESS and interaction indices offer the similar behaviours (e.g. having an ANDNESS index that is greater than 0.5 will give a positive interaction index value among those two indicators where indicators are evaluated as being complementary). However, for the case of sub-nodes that have more than two indicators, it is necessary to analyze both ANDNESS and interaction indices separately, since one sub-node may have an ANDNESS index greater than 0.5 but may consist of indicators having negative interaction indices (i.e. competitive) and some others having positive interaction indices (i.e. complementary).

Figure 3 illustrates the ANDNESS degree of each Decision Maker for the three final pillars and the FEEM SI node, showing that the evaluations of sustainability indicators at a given node do vary among different decision makers. Some Experts have similar attitude towards indicators at every pillar and the FEEM SI node (e.g., Expert 6 and Expert 14 have more *non-compensative* while Expert 15 have more *compensative* attitude towards all three final pillars and the FEEM SI node). Conversely, there are also Experts that have different attitudes depending on the pillar (e.g. Expert 1). We further present descriptive statistics of the ANDNESS degrees at Table 1.

⁹ Since deciding on expert selection and also process of data collection is costly, for this stage only a limited number of experts were consulted.

¹⁰ Meyer and Ponthière (2011) practice elicitation exercise which reveals a strong heterogeneity of individual preferences on hypothetical societies and examined how elicited preferences can be used to cast a new light on the ranking of actual societies. In the case of sustainability, elicitation is an important process for the evaluation of sustainability indicators and expert evaluations may differ in different societies and within societies, therefore, we derive “consensus” measures from many respondents. Moreover, we implement sensitivity analysis which allows linear combination of the measures from different respondents on sustainability levels to evaluate the robustness of the rankings and sustainability levels in section 4.4.

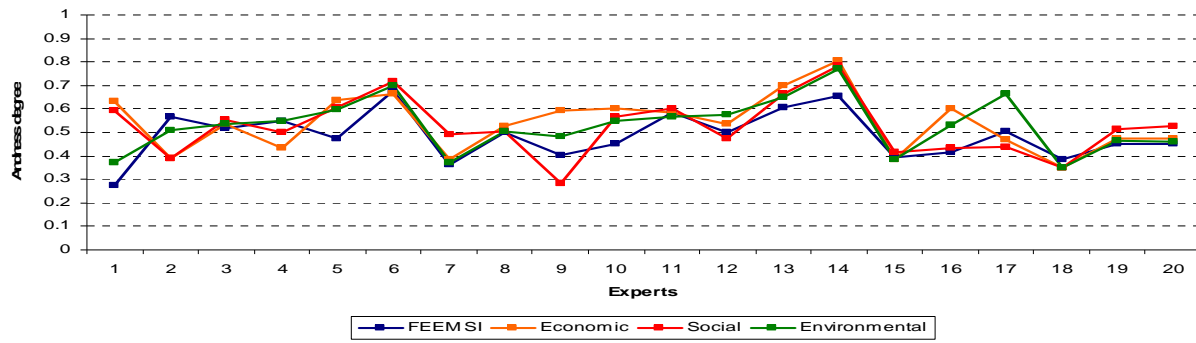


Figure 3: ANDNESS Degree of the Experts at the final pillars and the FEEM SI node

Table 1: Descriptive Statistics of the ANDNESS Degree of Experts

Node	Mean	Standard Deviation	Minimum	Maximum
FEEM SI	0.486	0.102	0.275	0.678
Economic Pillar	0.521	0.122	0.285	0.783
Social Pillar	0.538	0.120	0.350	0.805
Environmental Pillar	0.529	0.113	0.350	0.768

As detailed in section 3.3 and confirmed in the preliminary analysis of ANDNESS degree among experts, a consensus measure has been proposed in order to derive a general “consensus” attitude towards sustainability indicators at each sub-node. Table 2 shows the ANDNESS degree and the interaction indices among indicators at each sub-node for the “representative” decision maker. The first panel of the Table 2 presents the ANDNESS degrees and interaction indices for the 3-indicator sub-nodes and the second panel offers the same information for the 2-indicator sub-nodes.

Table 2 Panel A: Interaction indices and ANDNESS Degree at 3-indicator sub-nodes

Node	Interaction indices			ANDNESS degree
FEEM SI	Economic	Social	Environmental	0.493
Economic	NA	-0.024	0.020	
Social		NA	-0.019	
Environmental			NA	
Economic	Growth drivers	GDP pc	Exposure	0.538
Growth drivers	NA	0.047	0.026	
GDP pc		NA	0.041	
Exposure			NA	
Social	Pop. Density	Well being	Vulnerability	0.525
Pop. Density	NA	0.016	0.041	
Well being		NA	0.020	
Vulnerability			NA	
Environmental	Air pollution	Energy	Endowments	0.532
Air pollution	NA	0.021	0.037	
Energy		NA	0.037	
Endowments			NA	
Vulnerability	Food	Private Health	Energy Security	0.528
Food	NA	0.040	0.022	
Private Health		NA	0.022	
Energy Security			NA	

Table 2 Panel B: Interaction indices and ANDNESS Degree at 2-indicator sub-nodes

Node	Indicators	Interaction index	ANDNESS degree
Growth drivers	R&D, Capital Accumulation	0.058	0.529
Exposure	Relative trade, Public debt	0.187	0.5935
Well being	Education, Health	0.029	0.5145
Energy security	Imp. energy, Energy access	0.000	0.5
Air pollution	GHG p.c., CO2 Intensity	0.183	0.5915
Energy Use	Energy Intensity, Renewables	0.053	0.5265
Endowments	Biodiversity, Water	0.058	0.529
Biodiversity	Animal, Plant	0.171	0.5855

Despite the differences among experts highlighted for instance in Figure 3 and Table 1, the representative (consensus) decision maker has a tendency of being more ANDNESS-oriented, showing a positive interaction behaviour towards sustainability indicators in all sub-nodes with the exception of the final node of FEEM SI. The final node of FEEM SI has an ANDNESS degree of 0.493, which represents a slightly *compensative* attitude towards the final node of the FEEM SI tree. Moreover, interaction indices between economic and social and social and environmental indicators are -0.024 and -0.019 respectively and consensus DM evaluates those interactions slightly *competitive* (or substitutes). On the other hand, the interaction index between the economic and environmental pillar is 0.020, and the representative DM evaluate those pillars as slightly complementary indicators. For the remaining sub-nodes, the representative DM features an ANDNESS index that is greater than 0.5 (i.e. more *non-compensative* attitude towards the nodes) and a positive interaction index value among two indicators at a given node (i.e. two indicator being more *complementary*). In the nodes in which the representative DM has a more *compensative* attitude, the ANDNESS index varies between 0.5145 and 0.5915. Moreover, the interaction index among two sustainability indicators varies between 0.016 and 0.183, with the exception of the final node of FEEM SI. In particular, the nodes that show the highest ANDNESS index are exposure, air pollution and biodiversity. The representative DM evaluates indicators at those nodes as being more *complementary* and therefore, for a country to have a higher sustainability level, it needs to perform well in both indicators rather than simply having a satisfactory performance in only one of those.

4. Results and robustness analysis

In this section we will present only some of the FEEM SI results in order to describe the impacts of the aggregation methodology and provide examples of the importance of such methods in evaluating policy choices; for a more complete overview of the FEEM SI results please refer to the materials available online.¹¹

4.1 FEEM SI results using the Choquet integral as an aggregation operator

The hierarchical structure used to construct the FEEM SI allows obtaining the sustainability ranking for each year of analysis, including future projections of the sustainability levels, enlarging the scope of the analysis to policy implications. Since this paper focuses on the role of the aggregation methodology in dealing with sustainability, reported results refer only to the baseline scenario.¹² Table 3 presents the sustainability rankings of countries in the year 2011.¹³

¹¹ www.feemsi.org

¹² For further details and policy implications please refer to Carraro et al. (2012)

¹³ Current analysis considers individual countries (e.g., Norway) and macro-regions (e.g., Rest of Latin America). For detailed country and macro-region classification, see Table A.2.

Table 3: FEEM SI Ranking in 2011

Rank	Country	FEEM SI	Rank	Country	FEEMSI
1	Norway	0.823	21	Russia	0.493
2	Sweden	0.774	22	RoEU	0.493
3	Switzerland	0.700	23	Mexico	0.492
4	Austria	0.691	24	Korea	0.477
5	Finland	0.661	25	Italy	0.472
6	Denmark	0.653	26	Japan	0.456
7	Canada	0.641	27	Turkey	0.453
8	France	0.630	28	Middle East	0.450
9	Ireland	0.620	29	Poland	0.430
10	New Zealand	0.609	30	South Africa	0.426
11	USA	0.554	31	Greece	0.399
12	Australia	0.553	32	RoAfrica	0.398
13	Brazil	0.546	33	RoWorld	0.385
14	UK	0.531	34	SEastAsia	0.368
15	RoEurope	0.529	35	RoFSU	0.367
16	Germany	0.525	36	North Africa	0.342
17	Portugal	0.522	37	RoAsia	0.325
18	RoLA	0.512	38	Indonesia	0.299
19	Spain	0.497	39	China	0.287
20	Benelux	0.495	40	India	0.240

Benelux: Belgium, Netherlands, and Luxembourg; **RoAfrica:** Rest of Africa; **RoAsia:** Rest of Asia; **RoEU:** Rest of European Union; **RoEurope:** Rest of Europe; **RoFSU:** Rest of Former Soviet Union; **RoLA:** Rest of Latin America; **RoWorld:** Rest of World; **SEastAsia:** Southeast Asia

We also examine the partial scores obtained in the three main subcomponents and analyze whether there are general features that lead a country to be more sustainable; as shown in Figure 4, there is a marked tendency in the most sustainable countries to perform well in all three subcomponents, while the worst performers show very different performances in the three subcomponents. For instance, India and Indonesia perform worse in the social pillar than the other pillars whereas China is the worst performer in the environmental pillar.

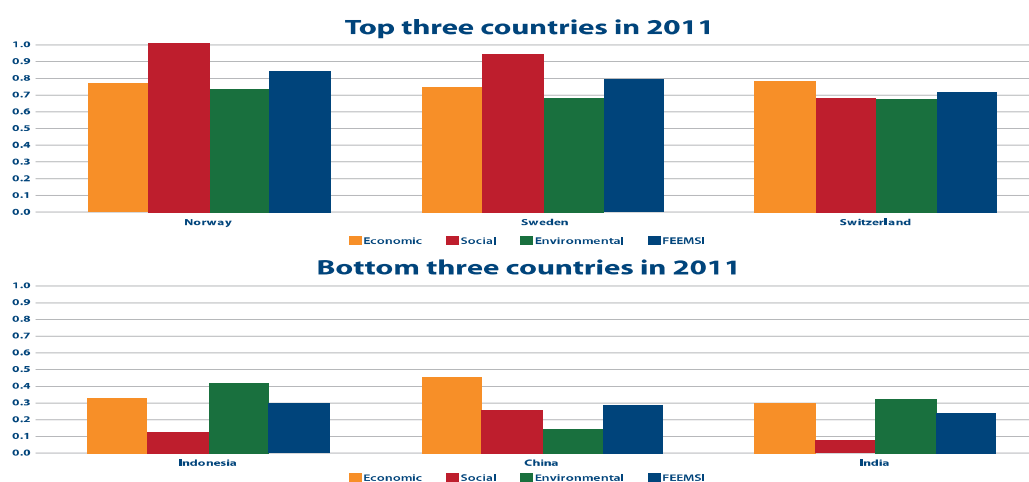


Figure 4: FEEM SI and sustainability pillars for the Top and Bottom Countries in 2011

This finding is not surprising as it is a reflection of the representative DM attitude which the Choquet integral aggregation methodology allowed us to introduce. Given that the representative DM used in this study show a pessimistic tendency (characterized by an *andness* score greater than 0.5 for almost in all sub-nodes) and each indicator is a *complementary* of other one(s) rather than a *substitute* at each sub-node (i.e. positive interaction indices), achieving a balanced performance will be rewarded much more than achieving a good one in only one component. This feature explains why some developed countries rank so low compared to other: in the case of the United States, for example manages only a 11th place, due to its extremely poor environmental performance (ranked 39th) relative to its good performances both in the economic and social components.

Table 4 offers the rankings of countries and macro-regions in the economic, social and environmental pillars. The first two columns are the FEEM SI and its ranking for the countries and macro-regions and the remaining columns represent the economic, social and environmental sustainability levels and their respective rankings. One interesting aspect of this ranking is that countries that are in the higher and lower ranking positions are the ones that have a better (worse) outcome at least in two final pillars respectively. For example, Norway and Sweden not only have outstanding sustainability levels in the social pillar, but have also quite good performances both in the economic and environmental pillars. Among the lower-ranking countries, India has an extremely poor performance in the social pillar and a poor performances in the economic and social pillars. China has a moderate economic performance, but features low social and environmental sustainability outcomes. Both Rest of Asia and Indonesia have a low performance in the economic and social pillars and moderate environmental performances. On the other hand, some countries achieve good results in some pillar(s), while their remaining pillar(s) lagged behind from many countries. For example, USA and Australia have better sustainability levels in economic and social pillars, but very poor levels of environmental performance. Moreover, Korea only achieves a better economic sustainability level, but has very bad performances in social and environmental aspect.

The results obtained through the FEEM SI aggregation procedure suggest variability of sustainability outcomes at different pillars of sustainability. To have a deeper understanding of why some countries achieved higher (lower) levels of sustainability overall and/or in different pillars, the next section will detail the relative importance of different indicators at a given sub-node level and their global importance for the final index.

Table 4: Sustainability pillars: Rankings in Economic, Social and Environmental Pillars in 2011

FEEM SI Rank	FEEM SI	Country	Economic	Econ. Rank	Social	Social Rank	Environ.	Envi. Rank
1	0.823	Norway	0.752	3	0.985	1	0.718	1
2	0.774	Sweden	0.728	5	0.922	2	0.664	2
3	0.700	Switzerland	0.766	1	0.668	12	0.661	3
4	0.691	Austria	0.700	7	0.755	9	0.623	5
5	0.661	Finland	0.686	8	0.799	6	0.512	10
6	0.653	Denmark	0.663	10	0.837	4	0.469	15
7	0.641	Canada	0.566	19	0.845	3	0.499	12
8	0.630	France	0.584	15	0.789	8	0.509	11
9	0.620	Ireland	0.666	9	0.683	11	0.528	8
10	0.609	New Zealand	0.591	13	0.829	5	0.411	24
11	0.554	USA	0.725	6	0.790	7	0.210	39
12	0.553	Australia	0.737	4	0.734	10	0.251	36
13	0.546	Brazil	0.446	26	0.603	17	0.597	6
14	0.531	UK	0.577	17	0.582	19	0.451	16
15	0.529	RoEurope	0.433	28	0.519	24	0.625	4
16	0.525	Germany	0.617	11	0.618	15	0.372	30
17	0.522	Portugal	0.458	23	0.646	14	0.449	17
18	0.512	RoLA	0.392	31	0.570	20	0.585	7
19	0.497	Spain	0.575	18	0.597	18	0.347	31
20	0.495	Benelux	0.611	12	0.480	29	0.396	26
21	0.493	Russia	0.586	14	0.511	25	0.393	27
22	0.493	RoEU	0.491	21	0.499	26	0.487	13
23	0.492	Mexico	0.435	27	0.656	13	0.374	29
24	0.477	Korea	0.761	2	0.330	34	0.312	33
25	0.472	Italy	0.404	30	0.559	21	0.446	19
26	0.456	Japan	0.581	16	0.351	33	0.420	22
27	0.453	Turkey	0.417	29	0.491	27	0.448	18
28	0.450	Middle East	0.558	20	0.543	22	0.283	35
29	0.430	Poland	0.463	22	0.538	23	0.304	34
30	0.426	South Africa	0.454	25	0.612	16	0.230	38
31	0.399	Greece	0.354	34	0.439	30	0.402	25
32	0.398	RoAfrica	0.279	40	0.378	32	0.523	9
33	0.385	RoWorld	0.306	37	0.405	31	0.445	20
34	0.368	SEastAsia	0.390	32	0.261	36	0.440	21
35	0.367	RoFSU	0.386	33	0.482	28	0.244	37
36	0.342	North Africa	0.350	35	0.285	35	0.385	28
37	0.325	RoAsia	0.285	39	0.185	38	0.477	14
38	0.299	Indonesia	0.331	36	0.127	39	0.419	23
39	0.287	China	0.455	24	0.260	37	0.147	40
40	0.240	India	0.301	38	0.077	40	0.328	32

4.2 Measure of relative importance of indicators

As pointed out in the previous section, the computation of the aggregated index strongly depends on the *subjective relative importance* of a coalition with respect to another one. Given the evaluations of sustainability indicators at each node, it is possible to infer the relative importance given to every sub-node at every node of the aggregation tree. This can be achieved by computing the Shapley values of the aggregation criteria (described in Appendix A), which amounts to compute the relative importance given to a every coalition of criteria. These results, obtained from the “representative” DM evaluations used to compute the FEEM SI values, are shown in Table 5.

Table 5: Relative importance of each indicator at a given node

Node	Criterion	Shapley value
FEEMSI	Economic	0.332
	Social	0.316
	Environmental	0.352
Economic	Growth drivers	0.378
	GDP per capita	0.355
	Exposure	0.267
Social	Population Density	0.254
	Well Being	0.415
	Vulnerability	0.331
Environment	Air pollution	0.351
	Energy	0.330
	Natural Endowment	0.319
Growth Drivers	R&D	0.522
	Investment	0.478
Exposure	Relative Trade Balance	0.554
	National Debt	0.446
Well Being	Education	0.508
	Health	0.492
Vulnerability	Food relevance	0.395
	Energy Security	0.275
	Private Health	0.330
Energy Security	Energy Imported	0.500
	Energy Access	0.500
Air pollution	GHG per capita	0.520
	CO ₂ Intensity	0.480
Energy	Energy Intensity	0.458
	Renewables	0.542
Natural Endowment	Biodiversity	0.455
	Water	0.545
Biodiversity	Animals	0.516
	Plants	0.484

These values reflect the *local* relative importance of sub-nodes at every level of the aggregation tree. For instance, it is possible to see that at the highest node (*FEEM SI*), greater relative importance is given to *environmental sustainability* (0.352) than to *economic sustainability* (0.332) or *social sustainability* (0.316).

It is also possible to combine these results in a linear fashion in order to approximate how much every final node of the aggregation tree contributes towards the determination of the final FEEM SI values. By multiplying the Shapley values of every hierarchically superior node of every indicator, from the bottom of the aggregation tree to the top (e.g., contribution of health is calculated by multiplying the Shapley values of health, well being and social pillar, since health indicator is under the node of well being which is a node of social pillar), we are able to determine the overall importance weights, ranked by decreasing value and summing to one. Table 6 offers the contribution of each indicator to the final index.

Both the structure of the tree and the evaluations provided by the DM determine the contribution of indicators to the final FEEM SI values. In this instance the indicator with the largest impact on the FEEM SI values is *GDP per capita*, which is at a distance of a node from the top of the aggregation tree, is placed besides only one other sub-node (*economic pillar*, not an indicator itself). Other indicators, being further away from the final index in the aggregation tree, being part of larger nodes and receiving lower individual valuations, contribute comparatively less to the determination of the FEEM SI values. For example, indicators that are located at the lowest sub-node (i.e., attributes that measure the animal and plant biodiversity, and countries' energy dependence and their access to the energy) are also the ones that contribute least to the final index.

Table 6: Indicator's contribution to overall index

Indicator	Contribution to overall index
GDP per capita	0.1179
Population Density	0.0803
Education	0.0666
R&D	0.0655
Health	0.0645
GHG per capita	0.0642
Renewables	0.0630
Water	0.0612
Investment	0.0600
CO2 Intensity	0.0593
Energy Intensity	0.0532
Relative Trade Balance	0.0491
Food relevance	0.0413
National Debt	0.0395
Private Health	0.0345
Animals	0.0264
Plants	0.0247
Energy Imported	0.0144
Energy Access	0.0144

4.3 FEEM SI Results using alternative aggregation operators

The results obtained so far stem from the application of the Choquet integral as an aggregation operator throughout the decision tree (see appendix for further details). In order to understand the impact of the aggregation method on the results of the final sustainability index, we apply alternative aggregation methods to the indicators and compare the results to those of the FEEM SI values. There are several alternative aggregation operators, each of which uses the available information (indicator values, tree structure and DM evaluations) in different ways.

At the simplest end of the spectrum, we can define a bottom-up equally-weighted average aggregation operator, called EWAb, which assigns the same weight to every indicator. In this instance, all 19 indicators receive a weight of $1/19 \cong 0.053$. This operator does not take into account the structure of the tree or the evaluation given by the DM and assumes compensability among indicators.

A slightly more refined version of the equally-weighted average operator involves weighting the indicators based on the structure of the tree (operator EWAt), starting from the top and giving equal weight to every *branch* of the aggregation tree until every indicator is reached and weighted accordingly. The indicators are then aggregated by a linear combination using those weights. Also in this case, the valuations of the DM are not taken into account and the indicators are assumed to be compensable.

Alternatively, one could use the *local* Shapley values of criteria described in the previous section as weights in a linear combination process. This approach would combine indicators taking into account the structure of the FEEM SI tree, and information derived from the DM evaluation, but would still be compensative in nature.

Finally, we can aggregate the indicators using the generalized mean. This aggregation operator can be applied to every node of the aggregation tree and depend on a single parameter p that represents the degree of substitutability among indicators. This approach uses the structure of the tree and, depending on p , can be non-compensative, but in its simplest case is applied uniformly to every component of a single node and does not use the evaluation provided by the

DM. For the purposes of aggregation, an arbitrary value of p has been chosen to perform the aggregation throughout the tree. Given that the evaluation of the DM does not provide precise information on the *overall* substitutability of indicators (apart from the monotonicity assumption that implies that indicators tend to be complements), the chosen value p^* has been found in such a way as to minimize the sum of square deviations of the final FEEM SI value with respect to the values obtained with the Choquet integral.

The rank of countries resulting from the application of these operators for the year 2011 is reported in appendix A (Table A.3), showing also the absolute difference in the rankings when compared with the rankings obtained by using the Choquet integral aggregation. These comparisons highlight the stark differences in rankings that all of the above-mentioned aggregation operators yield with respect to the Choquet integral. All of these aggregation operators yield up to 10-position changes in the ranking of some countries, providing conspicuous instances of rank reversal. The differences are arguably attributable to the subtlety of the aggregation under the Choquet integral, combined with the structure of the FEEM SI tree, which allows not only to assess each indicator and node on its own, but also to characterize interactions among indicators and nodes.

4.4 Robustness analysis

In a complex aggregation such as the one used for the FEEM SI, the attitude of the representative decision maker is a key component of the process. Thus, it is important to check how robust the ranking is to a change in the representative decision maker's attitude.

There exist many ways to modify the weights provided by the decision makers in the hierarchical decomposition (the decision tree); a straightforward way is to consider more than one such decision maker at the time, considering each of them as a point in the weight space. Then, a robustness analysis can be performed by building a linear convex combination of the values of the weights and run a significant number of simulations, as in a Monte Carlo approach. It is easy to prove that a linear convex combination of K different non-additive monotonic measure is an additive monotonic measure too.

The robustness analysis has been carried out by generating 1000 sets of measures that are necessary to aggregate the indicators into the final FEEM SI. Each of these sets constitutes, for any practical purposes, an internally consistent assessment on sustainability identical to what is provided by decision makers. These sets have thus been called "artificial decision makers" (ADMs). In this particular application, each ADM represent an univocal instance of consensus among "real" decision makers, whose measures have been combined using random weights, similarly to how the representative decision maker has been constructed. The measures contained in the artificial decision makers has been used to aggregate, with the Choquet integral, the FEEM SI, using the same indicators as for the reference case. The process results in a distribution of final FEEM SI for each country considered, which can be ranked according to the relative dominance measure ρ (derivation of the measure described in the appendix). The results of this simulation, on the 2011 FEEM SI data, are show in the Figure 5.

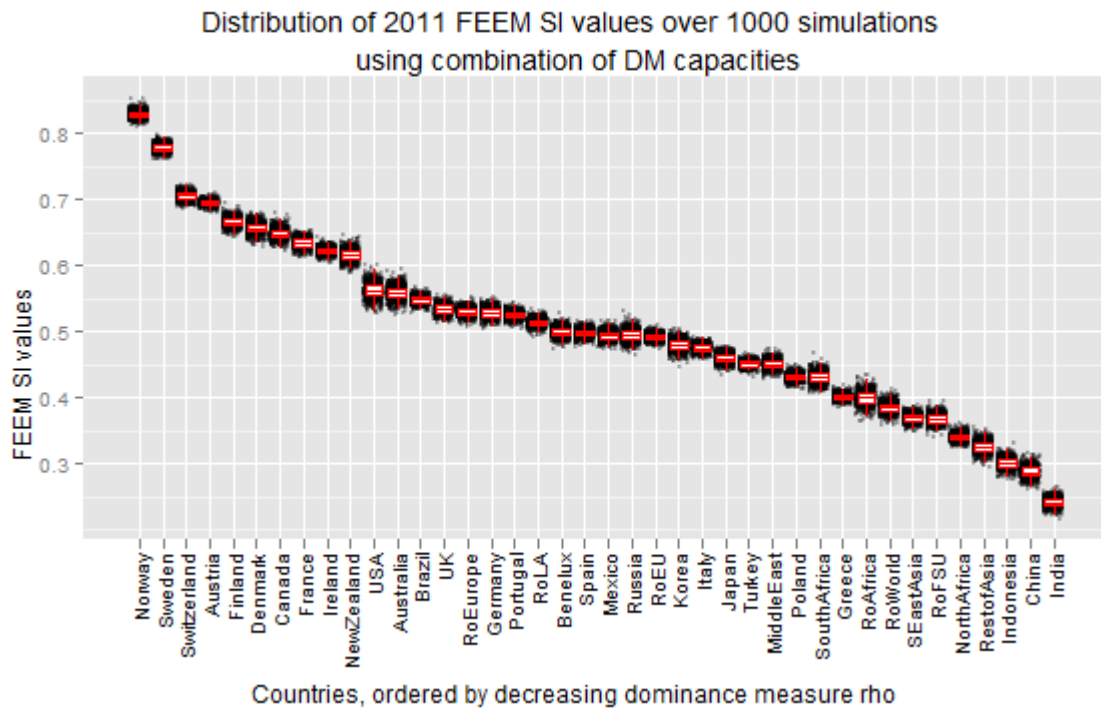


Figure 5: Distribution FEEM SI values according to 1000 artificial decision makers.

The plot displays the simulated values according to every ADM. The distribution of these is summarized by box-plots for every country. It can be seen that, within the “consensus” among decision makers – reflected any ADM, which results in a point of the distribution – some countries or groups of countries clearly “dominate” others in the ranking. One should be careful, however, whenever drawing inverse inferences from this analysis, since the distributions of simulated FEEM SI values are not independent from one another. This means that analyzing the ranking results merely by comparing the features of the distributions would not fully take into account the nature of the data and could possibly lead to misleading interpretations.

In particular, whenever any two given countries have simulated distributions that partially overlap each other, it is not necessarily the case that there is an underlying ambiguity over how these two countries are ranked according to the measures provided by ADMs. This stems from the fact that measures provided by single ADM (constructed from “real” decision makers) contributes to determine the FEEM SI values for every country. It is therefore necessary to analyze the simulation results using a measurement that takes into account the relationship between countries across simulations. The matrix, Δ , (representing average cardinal dominance) and the indices ρ^+ , ρ^- and ρ (representing, respectively, the degree to which a given country i dominates every other country, the degree to which a given country i is dominated by every other country and the relative dominance level of the country in question) have been designed for this purpose and the derivation of those are described in the appendix. These results, obtained for those indices for each country, for the 2011 FEEM SI data, are also reported in the appendix in Table A.4.

Considering the dominance analysis together with the plot of simulated distributions unveils some interesting results. For instance, it is clear that the leading countries, Norway and Sweden, are quite set apart from the rest of the group – and from each other. In fact, Norway happens to be never dominated by any other country across all simulations, a quite remarkable result given the variability introduced by the simulations. Norway and Sweden, are both followed by a

group of eight countries (Switzerland, Austria, Finland, Denmark, Canada, France, Ireland and New Zealand) which constitute a faction of relatively high-scoring countries. These feature a consolidated ranking among themselves, as measured by the dominance index across simulations, which is stable by construction. These countries are followed by two somehow discontinuous cluster of countries (from USA to South Africa and from Greece to China) featuring a less dramatic discontinuity among clusters. In last position, India never dominates any other country across simulations.

By nature of the dominance analysis, these results tend to produce a robust ranking and illustrate the extent to which a change in “consensus” among decision makers can result in variability in the score of countries, thereby adding a valuable complement to the “representative” decision maker constructed for the reference aggregation.

5. Conclusions

This paper aimed at proposing an application of non-linear aggregation methods to sustainability literature, extending the current work in this field to address the intrinsic complexity underlying the sustainability concept. The aggregation approach was inspired by two considerations: firstly, the non-compensative nature of the sustainability concept, fraught with inter-linkages and synergies across its different components. Secondly, the clear policy relevance of any sustainability analysis, which requires to involve the subjective judgements of policy makers and relevant stakeholders in order to define a feasible plan for the implementation of a new definition of world progress. This requires to manage the subjective character of the decision support tool. Combining the non-additive measure algorithm -a novelty in the field of sustainability analysis- with sensitivity analysis- a well-known approach for simulation- the scoring system for sustainability assessment has been improved with respect to other similar ones. Despite the unavoidable partial uncertainty of any scoring system, the method proposed fulfils two requirements that are necessary for a rational sustainability analysis: the monotonicity and the non-compensability assumptions. Robust options are enhanced by numerical simulation, as soon as some pillars are defined as basic measures with respect to such requirements. It is quite important that these properties be fully understood and accepted.

This paper also has interesting policy-making potential. In fact, using the method proposed in this paper, a complete sustainability ranking of the regions of the world has been proposed, both for the current and future years, exploiting the features of the ICES computable general equilibrium model. Thus, comparative static analysis both across countries and through time has been made possible- a novelty in the field of sustainability assessment that may have important policy-making applications.

The analysis has been completed by three further investigations: through the computation of the Shapley index, it has been possible to address the relative importance of different indicators, which could also be used in the future to refine the current sustainability tree. Secondly, ANDNESS and interaction indices highlight that the representative DM evaluates majority of the sustainability indicators as being more *complementary* and therefore, for a country to have a higher sustainability level, it needs to perform well in all indicators rather than simply having a satisfactory performance in only one of those. Finally, a robustness analysis has provided a measure of the subjectivity implied by the artificial decision makers developed, confirming the validity of the overall method in evaluating overall sustainability. Despite the importance of extending the current pool of decision makers involved in the analysis, the method proposed is already able to capture important information about sustainability, economizing on computational time without sacrificing too

much information –another important feature for policy-making applications.

Lastly, the comparison of the rankings obtained through the Choquet integral and other aggregation operators - some of which are much more frequently used in sustainability indices such as the EWA –has shown the ability of Choquet integral method to address subtle inter-linkages and connections across components, supporting the use of such methods for sustainability assessment.

As future development, it will be important to extend the pool of decision makers involved in the determination of the measures used in the aggregation operator. Extension of the pool of decision makers will not only allow for obtaining a more representative ‘consensus’ measures, but also for the evaluation of sustainability perceptions from different parts of the world. Given the heterogeneity of the current conditions (economic, social and environmental condition in general) in different countries (macro-regions), the need for future generations will vary and therefore importance given to sustainability indicators and their interactions may differ. If this is the case, a tool like the FEEM SI can offer different policy implications in different regions considered in the analysis.

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APPENDIX A

A.1 Non-Additive Measures and the Choquet Integral

In this section, we present the formal definition of NAM and the Choquet integral. To this purpose, let us consider the following Definition:

Definition 1. Let $N = \{1, 2, 3, \dots, n\}$ be the set of attribute for a given node in the tree. A *non additive (monotonic) measure* is a set function $m : S \subseteq N \rightarrow [0, 1]$, which satisfies:

$$m(\emptyset) = 0, m(N) = 1$$

$$\forall S, T \subseteq N : S \subseteq T \Rightarrow m(S) \leq m(T),$$

The two first constraints are two border condition, while the second represents a monotonicity constraint, a rational property. A NAM is *additive* if $m(S \cup T) = m(S) + m(T)$, $S \cap T = \emptyset$, while if $m(S \cup T) < m(S) + m(T)$, $S \cap T = \emptyset$, the measure is called *sub-additive*, implying a *redundancy* effect, and if $m(S \cup T) > m(S) + m(T)$, $S \cap T = \emptyset$ it is *super-additive* (a *synergic* effect).

The values of the criteria will be aggregated using the Choquet integral or similar methods like the *multi-linear* approach (Grabish 1995, 1996). Again, if the measure of all the subsets with the same cardinality is the same, the OWA is obtained (Ordered Weighted Averaging (Yager 1993)), and as particular cases the Min and the Max operators, the k-order statistics, their combination, and other ones. Let now (x_1, \dots, x_n) be the values of the (normalized) criteria, obtained from the benchmark filtering. Let $(x_{(1)}, \dots, x_{(n)})$ the ordered vector of the vector (x_1, \dots, x_n) , obtained by a suitable permutation of indices, so that $0 = x_{(0)} \leq x_{(1)} \leq x_{(2)} \leq \dots \leq x_{(n)}$ and $x_{(i)} \in (x_{(0)}, \dots, x_{(n)})$, $\forall i = 1, \dots, n$.

Definition 2. The Choquet integral of the vector (x_1, \dots, x_n) with $x_i \in [0, 1]$ with respect to the (non additive) measure $m : S \subseteq N \rightarrow [0, 1]$ is given by:

$$C_m(x_1, \dots, x_n) = \sum_{i=1}^n (x_{(i)} - x_{(i-1)}) \cdot m(A_{(i)})$$

being $A_{(i)} = \{i, i+1, i+2, \dots, n\}$, and $A_{(n+1)} = \emptyset$, $x_{(0)} = 0$. The same integral can be similarly written as:

$$C_m(x_1, \dots, x_n) = \sum_{i=1}^n x_{(i)} [m(A_{(i)}) - \mu(A_{(i+1)})]$$

showing that it extends the WA approach, given that it is the linear combination of the marginal gains between the ordered criteria, permitting to represent many aggregation operators, suitably tuning the values of the capacity. The Choquet integral is mathematically characterized by a set of properties and requirements, and can be alternatively

computed using the Möbius transform $\alpha_m(\mathbf{S})$ of the non additive measure, see (Grabisch et al., 2009) as follows:

$$C_m(x_1, x_2, \dots, x_n) = \sum_{T \subseteq N} \alpha_m(T) \cdot \min_{i \in T} \{x_i\}$$

where:

$$\alpha_m(\mathbf{S}) = \sum_{T \subseteq \mathbf{S}} (-1)^{|\mathbf{S}| - |T|} m(T), \quad \forall \mathbf{S} \subseteq N$$

are the Möbius coefficients associated to the capacity m .

Being that the *minimum* operator is the upper bound of a class of conjunctive operators, namely, the T-norm (*triangular norm*), which are monotonic operators that extend the logical conjunction to real values (*pessimistic* operator, in the sense that it computes the minimum of its arguments, independently on the values of the other ones; in this sense, it is a totally *non compensative* operator). In the computation of the Choquet integral using the Möbius representation, substituting the T-norm minimum with an other one, a different aggregation operator is obtained, the *multi linear* aggregation operator, similar to the Choquet integral for what it concerns the majority of characterizing properties. In particular, the T-norm *product* can be alternatively used, since, with respect to the minimum T-norm, is differentiable, and smoother, see Marichal (1998).

A.2 Shapley Value

The Shapley value characterizes the “relative importance” of each criterion and can be derived directly by the NAM values. The Shapley value can be computed for each criterion at every node of the hierarchy tree. It is obtained by averaging all the marginal gains obtained by adding the criterion to every coalition not including itself (Grabisch, 1995 and 1996).

For the *i-th* criterion, the Shapley value is calculated as follows:

$$v(i) = \sum_{T \subseteq N \setminus i} \frac{(n-t-1)!t!}{n!} [m(T \cup i) - m(T)] \quad \text{where } t = \text{card}(T)$$

These values have the property that $\sum_{i=1}^n v(i) = 1$. It is possible to verify that the Shapley values vary between 0 and 1, higher value representing higher importance of that criterion. It is also convenient to scale these values by a factor n , therefore, a value greater than 1 indicates an attribute more important than the average.

This value can be written alternatively as:

$$v(i) = \frac{1}{n} \sum_{T \subseteq N \setminus i} \frac{(n-t-1)!t!}{(n-1)!} [m(T \cup i) - m(T)] \quad \text{where } t = \text{card}(T)$$

$\frac{(n-t-1)!t!}{(n-1)!}$ being the inverse of the number of subsets with cardinality t . It follows that it can be interpreted as the

average of the marginal average gain of each coalition with the same cardinality.

A.3 ORNESS and ANDNESS Indices

It is clear that as soon as the measure values, $m(A_{(i)})$, are close to $(0,1,1,\dots,1)$, i.e. the maximum operator, the DM behaviour tends to be optimistic, and the contrary, as the measure values, $m(A_{(i)})$, are close to $(0,0,0,\dots,0,1)$, i.e. the minimum operator, the DM behaviour tends to be pessimistic.

To characterize whether DM follows more pessimistic or optimistic behaviour, it is possible to compute an index, depending solely on the measure values, the ORNESS index, together with the ANDNESS index. The former one measures the tendency to optimism, while the second one, measures the tendency to pessimism. Using the Möbius values of the measure, the ORNESS is computed as follows¹⁴:

$$ORNESS_m(i) = \frac{1}{n-1} \sum_{T \subseteq N} \frac{n-t}{t+1} a(T)$$

If ORNESS=1, then the DM is fully optimistic, implicitly using the maximum operator (logical disjunction), if ORNESS=0 (i.e. ANDNESS=1 since ORNESS+ANDNESS=1), then the DM is extremely pessimistic, corresponding to the minimum operator (logical conjunction), if ORNESS=0.5 the DM is additive in average.

A.4 Interaction Index

The intuition behind the interaction index is very similar to Shapley index but considering two indicators' contribution together rather than only one indicator's. Let's consider two indicators, i and j, and if the $m(i,j) > m(i) + m(j)$, then it shows a complementary effect between i and j. Similarly, $m(i,j) < m(i) + m(j)$ suggests that i and j interact in a redundant (substitutive) way. Finally, if $m(i,j) = m(i) + m(j)$, it can be considered that the indicators i and j do not interact, i.e., that they have independent roles.

To measure the all interaction of two indicators, the average interaction between two indicators i and j is calculated with the following interaction index (see Murofushi and Soneda, 1993):

$$I_m(ij) = \sum_{T \subseteq N \setminus ij} \frac{(n-t-2)!t!}{(n-1)!} [m(T \cup ij) - m(T \cup i) - m(T \cup j) + m(T)] \quad \text{where } t = \text{card}(T)$$

The outcome of $I_m(ij)$ can be considered as a measure of the average marginal interaction between i and j. One of the important property of the interaction index is that $I_m(ij) \in [-1,1]$ for all i and j. The interaction index being 1 (respectively -1) represents to full complementarity (resp. substitutivity) between i and j (see Grabisch, 1997).

¹⁴ The ANDNESS index can be computed also using the measure values, but the computation is more complicated, and it is not here reported.

A.5 Aggregation of Decision Makers

Let v_{ki} is the valuation (i.e. judgement) of k -th DM for i -th coalition at a given sub-node. Each sub-node have $2^n - 2$ possible coalitions that Decision Makers may have different judgements where n is the number of indicators at a given sub-node. One can calculate the distance measure of every DM's valuations to all other DMs' valuations at a given node.

Let us denote D_k , as the total absolute distance of k -th DM's judgements to all other DMs' judgements. D_k can be calculated as follows:

$$D_k = \sum_{i=1}^{i=2^n} \sum_{l=1}^{l=m} |v_{ki} - v_{li}|$$

where $l \neq k$, $l = 1, 2, \dots, m$ are the DMs, i is the valuation of a criterion or any possible combinations of criteria and n is the number of indicators at a given sub-node.

After calculating the absolute distance measure for each DM, we can find the sum of absolute distances of all DMs as:

$$\bar{D} = \sum_{k=1}^{k=m} D_k$$

Since absolute distance measures for all DMs and also the sum of absolute distance of all DMs are obtained for a given sub-node, (consensus) weights of each DM can be calculated. Each DM's weight is inversely related to the ratio of DM's absolute distance to the sum of all absolute distances. For instance, if a DM has the lowest absolute distance, that DM's valuations should be weighted more than the other DMs.

$$W_k = \left(\frac{D_k}{\bar{D}} \right)^{-1}$$

Weights given to each DM's evaluation can be further normalized so that the weights are bounded between 0-1.

$$w_k = \frac{W_k}{\sum_{k=1}^{k=m} W_k} \quad \text{where} \quad \sum_{k=1}^{k=m} w_k = 1$$

Since we have the normalized weights for each DM, one can obtain the "representative" DM valuations, v_i^r , for all possible coalitions at a given sub-node by weighted average of coalitions as:

$$v_i^r = \sum_{k=1}^{k=m} w_k v_{ki} \quad \text{for } \forall i \text{ where } i = 1, 2, \dots, 2^n$$

After obtaining representative measures for each coalition at each node of FEEM SI tree, the Choquet integral is used to aggregate all indicators to an overall index where the aggregation takes place at different stages starting from bottom nodes and ending at the final node.

A.6 Dominance analysis

As described in section 4.4, the analysis of the simulation results should take into account the fact that the distributions of simulated FEEM SI values are not independent from one another, since the data provided by single ADM contributes to determine the FEEM SI values for every country.

In order to describe more accurately the simulation results, the following measures have been implemented to compare any two countries i and j included in the ranking:

$$\Delta(i, j) = \frac{1}{N} \sum_{k=1}^k F[R_k(i) - R_k(j)]$$

where N is the number of countries included in the ranking, $R(i)$ and $R(j)$ are the FEEM SI values for the i^{th} and j^{th} country respectively. k is the number of simulations and $F(x)$ takes the form:

$$F(x) = \begin{cases} 0 & \text{if } x < 0 \\ x & \text{if } x \geq 0 \end{cases}$$

Constructed in this way, $\Delta(i, j)$ represents the ‘‘average cardinal dominance’’ of country i on country j . That is, the measurement expresses by how much, on average, the i^{th} country dominates the j^{th} across simulations. The overall dominance measure of country i on every other country is given by:

$$\rho^+(i) = \frac{1}{N-1} \sum_{j=1}^N \Delta(i, j)$$

Whereas the degree to which country i is dominated by every other country is given by

$$\rho^-(i) = \frac{1}{N-1} \sum_{j=1}^N \Delta(j, i)$$

We can thus construct the following measure:

$$\rho(i) = \frac{\rho^+(i)}{\rho^+(i) + \rho^-(i)}$$

which indicates the extent of relative dominance of the i^{th} country. This measures 1 if the country in question dominates any other across all simulations and measures 0 if country i is being dominated by all other countries. Being within the $[0,1]$ range, its interpretation is quite straightforward.

Table A.1: Sample questionnaire of the FEEM SI final node



Overall sustainability

You will have to rate the **sustainability** of some hypothetical scenarios.

In these scenarios, the following indicators can have a **GOOD or BAD performance**:

- **ECON**: Economic sustainability
- **SOC**: Social sustainability
- **ENV**: Environmental sustainability

Please **rate on a 0-100 scale** all of the following hypothetical situations.

Remember: a scenario where TWO indicators have a "GOOD PERFORMANCE" must be rated at least as the maximum score assigned to a scenario where only ONE of these TWO indicators have a "GOOD PERFORMANCE"

drag to determine your evaluation

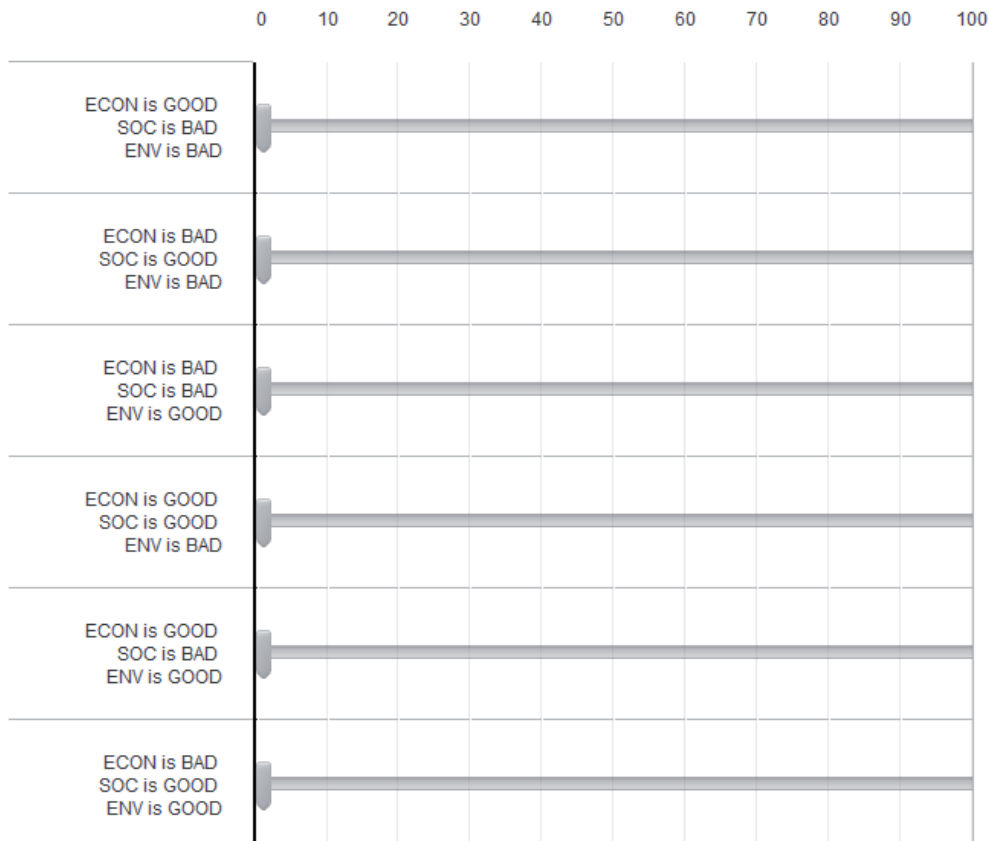


Table A.2: List of countries and macro-regions

No.	Macro-Regions	Countries
1	Australia	Australia
2	New Zealand	New Zealand
3	Japan	Japan
4	Korea	Korea
5	China	China, Hong Kong, Taiwan
6	India	Indonesia
7	Indonesia	India
8	SEastAsia	Malaysia, Philippines, Singapore, Thailand, Vietnam
9	RoAsia	Afghanistan, Bangladesh, Bhutan, Brunei Darassalam, Cambodia, Democratic Republic of Korea, Lao People's Democratic Republic, Macau, Maldives, Mongolia, Myanmar, Nepal, Pakistan, Sri Lanka, Timor Leste
10	USA	USA
11	Canada	Canada
12	Mexico	Mexico
13	Brazil	Brazil
14	RoLA	Argentina, Bolivia, Chile, Colombia, Ecuador, Paraguay, Peru, Uruguay, Venezuela, Falkland Islands (Malvinas), French Guiana, Guyana, Suriname, Costa Rica, Guatemala, Nicaragua, Panama, Belize, El Salvador, Honduras, Saint Vincent and the Grenadines, Trinidad and Tobago, Turks and Caicos, Anguilla, Antigua & Barbuda, Aruba, Bahamas, Barbados, Cayman Islands, Cuba, Dominica, Dominican Republic, Grenada, Guadeloupe, Haiti, Jamaica, Martinique, Montserrat, Netherlands Antilles, Puerto Rico, Saint Kitts and Nevis, Saint Lucia, Virgin Islands (British), Virgin Islands (U.S.)
15	Austria	Austria
16	Benelux	Belgium, Luxembourg, Netherlands
17	Denmark	Denmark
18	Finland	Finland
19	France	France
20	Germany	Germany
21	Greece	Greece
22	Ireland	Ireland
23	Italy	Italy
24	Poland	Poland
25	Portugal	Portugal
26	Spain	Spain
27	Sweden	Sweden
28	UK	UK
29	RoEU	Cyprus, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Malta, Malta, Slovakia, Slovenia, Bulgaria, Romania
30	Switzerland	Switzerland
31	Norway	Norway
32	RoEurope	Albania, Andorra, Bosnia and Herzegovina, Croatia, Faroe Islands, Gibraltar, Iceland, Liechtenstein, Macedonia, the former Yugoslav Republic of, Monaco, San Marino, Serbia and Montenegro
33	Russia	Russia
34	RoFSU	Belarus, Ukraine, Moldova, Republic of, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan, Armenia, Azerbaijan, Georgia
35	Turkey	Turkey
36	MiddleEast	Bahrain, Islamic Republic of Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Occupied Palestinian Territory, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, United Arab Emirates, Yemen
37	North Africa	Algeria, Egypt, Libyan Arab Jamahiriya, Morocco, Tunisia
38	RoAfrica	Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Democratic Republic of the Congo, Cote d'Ivoire, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mayotte, Mozambique, Niger, Nigeria, Reunion, Rwanda, Saint Helena, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, Sudan, Swaziland, Tanzania, Togo, Uganda, Zambia, Zimbabwe
39	South Africa	South Africa
40	RoWorld	American Samoa, Cook Islands, Fiji, French Polynesia, Guam, Kiribati, Marshall Islands, Micronesia, Federated States of, Nauru, New Caledonia, Norfolk Island, Northern Mariana Islands, Niue, Palau, Papua New Guinea, Samoa, Solomon Islands, Tokelau, Tonga, Tuvalu, Vanuatu, Island of Wallis and Futuna, Bermuda, Greenland, Saint Pierre and Miquelon

Table A.3: Comparison of alternative aggregation operators for the year 2011

Country	Rank FEEMSI	Rank EWAb	Δ ranking wrt Choquet	Rank EWAt	Δ ranking wrt Choquet	Rank GM(p*)	Δ ranking wrt Choquet
Australia	12	13	-1	11	+1	25	-13
Austria	4	4	=	3	+1	3	+1
Benelux	20	14	+6	23	-3	24	-4
Brazil	13	16	-3	13	=	14	-1
Canada	7	8	-1	7	=	10	-3
China	39	38	+1	39	=	37	+2
Denmark	6	6	=	6	=	7	-1
Finland	5	5	=	5	=	5	=
France	8	7	+1	10	-2	8	=
Germany	16	15	+1	18	-2	15	+1
Greece	31	35	-4	33	-2	30	+1
India	40	40	=	40	=	40	=
Indonesia	38	39	-1	38	=	39	-1
Ireland	9	9	=	8	+1	9	=
Italy	25	27	-2	28	-3	20	+5
Japan	26	28	-2	30	-4	29	-3
Korea	24	20	+4	26	-2	28	-4
Mexico	23	25	-2	22	+1	22	+1
MiddleEast	28	26	+2	24	+4	21	+7
NewZealand	10	10	=	9	+1	13	-3
NorthAfrica	36	33	+3	35	+1	32	+4
Norway	1	1	=	1	=	1	=
Poland	29	29	=	29	=	23	+6
Portugal	17	21	-4	20	-3	16	+1
RoAfrica	32	32	=	31	+1	36	-4
RoAsia	37	37	=	37	=	38	-1
RoEU	22	18	+4	19	+3	17	+5
RoEurope	15	11	+4	15	=	6	+9
RoFSU	35	34	+1	34	+1	34	+1
RoLA	18	19	-1	16	+2	11	+7
RoWorld	33	31	+2	32	+1	35	-2
Russia	21	17	+4	14	+7	27	-6
SEastAsia	34	36	-2	36	-2	31	+3
SouthAfrica	30	30	=	27	+3	26	+4
Spain	19	23	-4	21	-2	19	=
Sweden	2	2	=	2	=	2	=
Switzerland	3	3	=	4	-1	4	-1
Turkey	27	24	+3	25	+2	12	+15
UK	14	12	+2	17	-3	18	-4

Table A.4: Ranking of countries according to average dominance index across simulated values, ρ , for 2011 FEEM SI

Country	ρ^+	ρ^-	ρ
Norway	8.272517	0	1
Sweden	7.017498	0.032180	0.995435
Switzerland	5.241969	0.125629	0.976595
Austria	4.993397	0.145784	0.971633
Finland	4.322133	0.220431	0.951474
Denmark	4.124075	0.249059	0.943048
Canada	3.932928	0.282739	0.932931
France	3.632407	0.346158	0.912994
Ireland	3.381697	0.409414	0.892007
NewZealand	3.264846	0.443318	0.880448
USA	2.244132	0.783920	0.741114
Australia	2.171497	0.811651	0.727921
Brazil	1.979238	0.893875	0.688883
UK	1.738591	1.010101	0.632516
RoEurope	1.671711	1.049046	0.614429
Germany	1.658449	1.056061	0.610957
Portugal	1.592388	1.097545	0.591980
RoLA	1.427004	1.218559	0.539395
Benelux	1.221855	1.392268	0.467405
Spain	1.206080	1.406183	0.461699
Mexico	1.163242	1.451047	0.444955
Russia	1.163253	1.453589	0.444526
RoEU	1.130448	1.487507	0.431806
Korea	0.994921	1.667540	0.373685
Italy	0.950801	1.733224	0.354245
Japan	0.801836	1.979846	0.288256
Turkey	0.725650	2.124143	0.254632
MiddleEast	0.722531	2.130927	0.253212
Poland	0.572879	2.479087	0.187708
SouthAfrica	0.568334	2.491081	0.185766
Greece	0.383163	3.049703	0.111616
RoAfrica	0.372474	3.087105	0.107665
RoWorld	0.294316	3.390436	0.079874
SEastAsia	0.226390	3.716297	0.057420
RoFSU	0.221337	3.745096	0.055803
NorthAfrica	0.132058	4.360702	0.029393
RestofAsia	0.094577	4.698028	0.019734
Indonesia	0.046588	5.290119	0.008730
China	0.029825	5.608623	0.005290
India	0	6.771014	0

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