Benefit-Cost Analyses and Toolkits

Combined MC-CBA methodology for decision making on Smart Grid

Discussion Paper

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ISGAN Annex 3

Task 4.5

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Preface

IEA-ISGAN Annex 3 started Task 4 with the aim to evaluate existing approaches for decision making applied to Smart Grid, and to propose new approaches as needed for quantitative analysis projected to 2050 by comparing a range of scenarios that differ for the level of smart grids deployment on different scales (i.e., local, regional, national and transnational).

Particularly, Subtask 4.5 deals with socioeconomic benefits of smart grids and looks at the relevant regulatory implications. Cost-benefit analysis is crucial in evaluating different regulatory options where the socio-economic perspective is of the outmost relevance. New market functionalities and strengthened interconnections between countries go beyond national borders and need regulators to collaborate making the societal cost-benefit analysis a more complex exercise. The scope of Subtask 4.5 is the identification of social benefits, the definition of suitable metrics for social benefits, and the assessment of the implications on regulation.

Three deliverables have been published with the aim to identify existing gaps and shortcomings in current cost-benefit analysis when applied to Smart Grid projects, to include new metrics for the assessment of benefits that with Smart Grids are not uniformly shared amongst the stakeholders and, finally, to propose new tools that can further improve the CBA with Multi criterial analysis that can fill some of the gaps of CBA and is better suited to non-monetizable and asymmetrical benefits.

- Deliverable 1 - Social costs and benefits of Smart Grid technologiesds
- Deliverable 2 - Asymmetric benefits of Smart Grids
- Deliverable 3 - Combined MC-CBA methodology for decision making on Smart Grid

As part of the overall effort taken in subtask 4.5, deliverable 3 analyses the weaknesses of the CBA and investigates the MCA approach. With the aim to outclass the CBA shortcomings, this discussion paper proposes to integrate the CBA into an MCA assessment framework. The ISGAN CBA toolkits can be easily combined with the proposed CBA-MCA. The proposed approach preserves the strengths of both CBA and MCA and identifies the best alternative according to its monetary and non-monetary performances. The MC-CBA methodology helps the decision maker identify the best Smart Grid investment option; the final aim is to provide a reliable support tool for orienting effectively the investments and the regulatory policies on Smart Grids.

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Nomenclature or List of Acronyms

AEEGSI	Autorità per l'Energia Elettrica, il Gas ed il Sistema Idrico (Italian Energy Authority)
AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
BAU	Business As Usual
CBA	Cost-Benefit Analysis
CBR	Cost Benefit Ratio
CR	Consistency Ratio
DM	Decision Maker
EC	European Commission
ELECTRE	ELimination Et Choix Traduisant la REalité
EPRI	Electric Power Research Institute
EU	European Union
FAA	Full Aggregation Approach
GAA	Goal Aspiration Approach
IRR	Internal Rate of Return
JRC	Joint Research Centre
KPI	Key Performance Indicator
MACBETH	Measuring Attractiveness by a Categorical-Based Evaluation TecHnique
MADM	Multi-Attribute Decision Making
MAUT	Multi-Attribute Utility Theory
MCA	Multi-Criteria Analysis
MCDA	Multi-Criteria Decision Analysis
MODM	Multi-Objective Decision Making
MUS	Marginal Utility Score
NPV	Net Present Value
OA	Outranking Approach
OC	Opportunity Cost
PM	Performance Matrix
PROMETHEE	Preference Ranking Organization METHod for Enrichment Evaluation
REMBRANDT	Ratio Estimation in Magnitudes or deci-Bells to Rate Alternatives which are Non- DominaTed
SCBA	Societal Cost-Benefit Analysis
TOPSIS	Technique of Order Preference Similarity to the Ideal Solution
US	Utility Score
WTA	Willingness to Accept
WTP	Willingness to Pay

Abstract

Smart grid projects are responsible of wide range impacts, which span from the electrical power system to the entire society. In general, the investment projects are assessed with a Cost-Benefit Analysis (CBA), which requires quantifying the impacts for converting them in monetary terms. In the smart grid context, not all impacts are quantifiable and/or monetizable; therefore, the CBA lacks in describing completely the smart grid potential. With the aim to outclass the CBA shortcomings, this discussion paper proposes to integrate the CBA into a Multi-Criteria Analysis (MCA) framework. The combined approach preserves the strengths of both CBA and MCA and identifies the best alternative according to its monetary and non-monetary performances. Furthermore, the stakeholders' point of view is directly collected and the preferences are explicitly related to the decision-making problem under analysis. To achieve a common smart grid assessment framework, the MC-CBA methodology relies on acknowledged guidelines on project analysis. The assessment approach described in this report decomposes the decision-problem by analysing the impacts in three main areas: the economic area, the smart grid development merit area, and the externalities area. The MC-CBA methodology helps the decision maker identify the best smart grid investment option; the final aim is to provide a reliable support tool for orienting effectively the investments and the regulatory policies on smart grids.

Executive Summary

This discussion paper has been developed within the sub-task 4 activities of the ISGAN Annex 3. Since smart grids impacts require new assessment approaches, this report aims at contributing on the debate about the evaluation of costs and benefits of smart grid projects. For the assessment of smart grid development options, a decision support tool is proposed. The Multi-Criteria Analysis (MCA) and the Cost-Benefit Analysis (CBA) are combined with the aim of supporting both regulatory bodies and stakeholders of the projects.

Traditionally in the electric power system, the assessment of investment options is made by means of the CBA. The CBA methodology has been developed for the financial evaluation of industrial projects (financial CBA). CBA is an acknowledged powerful tool if it is used in the private sector considering only cost and benefits that can be directly monetised. In contrast, CBA shows some drawbacks in the assessment of investment options which produce a not negligible share of the intangible impacts. In public sectors, the investment projects produce a relevant share of externalities and intangible impacts; therefore, the weaknesses of the CBA are emphasised. The main CBA shortcomings are related to the techniques for quantifying and monetising the intangible impacts. In addition, because of the discounting mechanism the CBA underestimates the effects of the future non-monetary impacts. Despite the disadvantages, the CBA allows to assess the investment spending efficiency; therefore, the use of this tool for evaluating the economic viability of the projects is desirable.

Unlike CBA, the MCA does not require to express all impacts in monetary terms. Furthermore, MCA allows the qualitative assessment of intangible impacts. MCA is a systematic approach which supports the decision maker (DM) in identifying the preferred design/development option. MCA considers several mutually conflicting evaluation criteria whose relevance depends on the DM's point of view. Since the identified best option maximises the fulfilment of the evaluation criteria, MCA may be not able for limiting the expenses.

Basically, a MCA technique is an algorithm that makes the overall assessment of the given alternatives on the basis of the input data provided in terms of performance scores and weights of the evaluation criteria. The key features are the performance matrix (PM), the hierarchy of criteria, and the stakeholders' point of view which gives subjectivity at the outcome of the analysis. The entries of the PM resume the performances of the alternatives on each criterion, the structure of the criteria hierarchy decomposes the overall decision-making problem, the preferences of the stakeholders are useful for defining the criteria mutual relevance. The scoring and the weighting stages are the key steps of a MCA: in the former the performances of the alternatives are converted to numerical scores, while in the latter a numerical value that reflects the relative importance is assigned to each criterion. The most suitable scoring and weighting techniques have to be chosen on the basis on the MCA method which is used for the assessment; the report describes some of the most acknowledged techniques.

The great diversity of real decision problems has led to a large number of MCA methods. Basically, MCA is composed of two main groups of methods: Multi-Objective Decision Making (MODM) and Multi-Attribute Decision-Making (MADM). MODM methods face

continuous multi-criteria problems where the number of alternatives is not explicitly known. Conversely, MADM methods are suitable for multi-criteria decision problems whose goal is to find the best alternative among a set explicitly known. Due to their features, this report is focused on the MADM methods. The MADM methods can be classified according to their approach in three main families: full aggregation approach (FAA), outranking approach (OA), and goal, aspiration or reference level approach (GAA).

The Analytic Hierarchy Process (AHP) is a FAA method widely used in decision-making problems. AHP is a fully-structured method which handles simultaneously quantitative and qualitative input data. Key features of AHP are the hierarchical decomposition of the decision problem, the ratio scale used for express preferences, and the pairwise comparison process which is used both for the scoring and the weighting stages. A linear additive model is used to combine scores and weights for evaluating the overall worthiness score of each alternative. The best alternative of the analysed set is the one that achieves the highest overall score.

Multi-Attribute Utility Theory (MAUT) methods are the FAA techniques which model the DM preferences by means of a utility function. The underlying hypothesis relies on the DMs tendency to optimise the function which aggregates his own preferences; this behaviour may be conscious or not. The utility function evaluates the extent to which each alternative is attractive to the DM. The Linear Additive Model (LAM) is the simpler way to define the utility function, it involves a linear relationship among performance scores and criteria weights. MAUT methods require a scoring stage of the PM and a weighting stage for assessing the criteria weights.

The outranking methods are based on the concept of outranking that allows to identify the dominant alternative. An alternative outranks another if it has better performances on criteria of enough importance, while its performances on the remaining criteria are not extremely inferior. To define the outranking binary relation, the alternatives are pairwise compared in terms of their performances. The DM’s view point is modelled by criteria weights which influence the dominance relationship between each pair of alternative. In addition, several thresholds related to the intensity of the performances on each evaluation criteria have to be defined by the DM. Among the outranking methods, the ELECTRE family is one of the main branches. Unlike AHP, the ELECTRE methods are not fully structured; therefore, the use of specific weighting techniques is required. Moreover, since the performances are handled by means of an interval scale, the scoring stage is not required for quantitative input data. ELECTRE III is one of the most acknowledged methods, its algorithm is divided into two stages: the computation of the outranking relationships and the exploiting of the obtained relationships. In the first stage, the outranking relationship of each pair of alternatives is built according to their performances, the criteria weights, the preference, the indifference, and the veto thresholds. In the second stage, the outranking relationships are analysed for identifying the dominant set of alternatives. The outranking relationship is described by the outranking degree which measures the strength of the outranking relationship.

With the aim to manage the input data imprecision of the decision-making problems, the use of the fuzzy set theory has been introduced in MCA. Fuzzy sets represent qualitative data and preferences by means of membership functions which model the vagueness of the natural language. Therefore, the attractiveness of an option can be quantified by means of a fuzzy number between [0, 1]. In fuzzy-MCA methods, performances and weights are expressed and managed in terms of fuzzy numbers; typically, the methodological framework is inherited from the corresponding MCA technique devised for crisp numbers. Due to their higher complexity, fuzzy-MCA methods are not widely employed in practice, their use is limited to academic studies.

Both CBA and MCA are comparative approaches for assessing the goodness of the investment alternatives. Regardless the differences between CBA and MCA, these two assessment approaches are not mutually exclusive, a joint use can be useful with the aim of relieving the respective lacks. In Literature, several combined assessment frameworks are proposed but despite its potential advantages, the joint use MCA-CBA it is not yet widely diffused. The joint analysis has been introduced with the aim to:

- outclass the lack of CBA on the stakeholders' preference modelling;
- outclass the lack of MCA on the economic assessment;
- outclass the weaknesses of CBA in the evaluation of the intangible impacts;
- promote an active participation of stakeholders in the decision-making.

In this report, a joint MC-CBA methodology is proposed for the assessment of smart grid development alternatives. This combined approach relies on the assessment guidelines for smart grid projects developed by the Joint Research Centre (JRC) and the Italian Regulator. The proposed methodology involves a CBA focused only to tangible impacts, while intangible impacts are evaluated by means of a MCA method. Since the flexibility of the MCA framework, CBA constitutes an input of the overall MCA. The joint evaluation tool guarantees a better analysis of complex decision-making problems which involve a great share of intangible impacts and externalities. The proposed MC-CBA approach decomposes the decision-making problem in a hierarchical structure. Three different area of interest are investigated: economic effects, enhanced smartness of the grid, and externalities. Each area constitutes an independent branch of the hierarchical structure. The evaluation criteria which compose the hierarchy have to reflect the way of achieving the main goal according to the core values of the company or the organisation which aims at it. The hierarchical structure is organised according to the principle of abstraction. The terminal criteria of each branch evaluate qualitatively or quantitatively the impacts of the project options. By combining performances and criteria weights through a MADM technique the outcome of the MC-CBA framework is obtained. The project option which better satisfies the DM's expectations is identified as the solution of the decision-making problem.

The overall evaluation of the project options is obtained by combining the results of the assessment on the three different branches. The economic evaluation branch aims at assessing the economic performance of the project options. The proposed approach involves a CBA of monetary impacts that may follow the procedure defined by JRC. The economic performances can be represented by means of the indices computed by CBA, or explicitly considering the items of monetary cost and benefits in the tree. The smart grid deployment merit branch evaluates the contribution towards the smart grid realization given by the project options. The evaluation of this impact area is based on the list of benefits for the energetic sector related to the smart grid development defined by the European Commission. Accordingly, the *policy criteria* and the related *Key Performance Indicators* defined by the JRC are used as evaluation criteria of the smart grid deployment merit branch. The third branch of the overall structure concerns the assessment of the project options in terms of externalities. Smart grid projects can produce externalities in several thematic areas (e.g., environmental, societal); accordingly, single externality impacts may be aggregated. Therefore, each second level criterion describes a thematic area, while the terminal criteria assess the magnitude of the single impacts originated by the alternatives.

The proposed MC-CBA assessment framework allows to assess the wide range impacts which a smart grid project option produces. Furthermore, the comparative approach allows to compare several project alternatives with the aim to identifying the best one according to the stakeholders' preference. Furthermore, the mixed qualitative-quantitative analysis requires less resources than an equivalent overall CBA assessment. In addition, impacts which a CBA neglects are also included in the assessment.

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1 Introduction

Currently, the Cost-Benefit Analysis (CBA) is the prominent tool for project assessment and decision aiding in the financial sector. To illustrate, the European Commission (EC) requires the CBA to appraise the effectiveness of smart grid deployment projects. Despite the advantages of CBA, it shows several drawbacks when project assessment involves non-monetary effects. In some societal analysis, those shortcomings can lead to unsound results.

Multi-Criteria Analysis (MCA) and CBA can be considered as complementary methodologies. To illustrate, intangible aspects as societal and environmental issues are directly handled in MCA since the monetisation of all impacts it is not compulsory. Moreover, the aim of MCA tools is to find the alternative that achieves the highest performances, hence the cost effectiveness of the result provided is not guaranteed.

Smart grid projects are responsible of wide range impacts which span from the electrical power system to the entire society. In the smart grid context, not all impacts are quantifiable and/or monetizable; therefore, the CBA lacks in describing completely the smart grid potential. Since the smart grids impacts require new assessment approaches, this discussion paper aims at contributing on the debate of the evaluation of costs and benefits of smart grid projects

In the following, CBA and MCA as decision making support tool are described. Advantages and drawbacks of both methodologies are highlighted, the aim is to propose a joint use that emphasises the strengths of both tools.

Then, a combined MC-CBA methodology for the assessment of smart grid development alternatives is presented. The MC-CBA approach identifies the best alternative according to its monetary and non-monetary performances. The assessment approach described in this report decomposes the decision-problem by analysing the impacts in three main areas: the economic area, the smart grid development merit area, and the externality area.

The MC-CBA methodology helps the decision maker in identifying the best smart grid investment option; the final aim is to provide a reliable support tool for orienting effectively the investments and the regulatory policies on smart grids.

2 Cost-Benefit Analysis

2.1 Introduction

Generally, the financial assessment of the industrial investment projects is made by a CBA which is based on the principles of neoclassical welfare economics [1]. The systematic assessment framework provided by CBA seeks for the most profitable investment alternative. Normally, the evaluation of industrial projects involves only financial aspects related to the investor. Those aspects consist in the monetary and/or direct monetizable impacts produced by the considered investment alternative.

The CBA involves several steps, that can be conceptually resumed as [2]:

- Recognition of all relevant aspect connected to the investment project;
- Recognition of the economic effects of the investment project;
- Conversion of cost and benefits in monetary terms;
- Evaluation of the algebraic sum of costs (negative effects) and benefits (positive effects);
- If the net value obtained is positive, the investment alternative is economically viable.

By means of CBA, it is possible to compare several alternatives; the most advantageous one achieves the greater value of the evaluation indices computed as output. Therefore, CBA is a fundamental decision aid tool for the planning process.

Despite its broad use in the private sector, the assessment by CBA of large infrastructural projects that involve public bodies is not fully acknowledged. Political bodies perform decision-making processes from a societal perspective; in this context, the weaknesses of CBA are highlighted because the assessment of societal impacts by means of a monetary-based tool shows several conceptual flaws [3].

Although its shortcomings, the Societal Cost-Benefit Analysis (SCBA) plays an important role in selecting the projects worth to be funded. With the aim to offer a common assessment framework, SCBA guidelines have been devised by government bodies of several countries. In general, each SCBA guideline is sector-specific even though are based on the same fundamental concepts [4].

2.1.1 Steps of the CBA

2.1.1.1 Target and context appraisal

The first step of the CBA requires defining the target to reach through the investment, along with the related cost and benefits. For the smart grid assessment, several systematic approaches have been devised by EPRI and JRC (Electric Power Research Institute and Joint Research Centre, respectively) helpful for identifying the benefits related to the features of the asset under analysis. The context appraisal involves the audit of the territory, stakeholders, and time horizon.

2.1.1.2 Quantification of cost and benefits

Next to the identification, costs and benefits are quantified in terms of the related unit of measurement.

2.1.1.3 Monetising and discounting of cost and benefits

In order to make cost and benefit comparable, CBA requires that all items are converted in monetary terms. To define the monetary value of quantified benefits, two different techniques are broadly employed: Willingness to Pay (WTP) and Willingness to Accept (WTA). The monetary value of quantified costs is evaluated by means of the Opportunity Cost (OC) approach [2]. Afterwards, each item is discounted to obtain its equivalent monetary value in the reference year.

2.1.1.4 Evaluation of the CBA output indices

Since discounted costs and benefits have been obtained, the economic indices provided as output by CBA can be computed. The most important indices are 3:

- Net Present Value (NPV);
- Internal Rate of Return (IRR);
- Cost Benefit Ratio (CBR).

NPV represents the net benefit produced by the investment alternative. A positive NPV means that the project produces more benefits than costs, thus the investment alternative is economically viable for investors. The IRR is the discount rate value that makes the NPV equal to zero. An investment alternative is considered as economically viable if its IRR is greater than the discount rate. CBR is evaluated as the ratio of the present value of benefits on the present value of costs. NPV, IRR and CBR provide complementary information about the investment alternative: the former is a measure of the profitability, the second is related to the quality, the latter represents the efficiency of the investment [5].

2.1.1.5 Sensitivity analysis

The last step of the CBA is the sensitivity analysis in which the robustness of the results is assessed with respect to the parameters. The robustness of each investment option is tested within the expected range of the parameters in order to find the alternative that best fits for the future scenarios [2].

2.1.2 Monetisation of cost and benefits

According to neoclassic economics, the impacts on social welfare of the availability changes of each good is measured by the willingness to pay of the stakeholders to obtain an increase or to avoid a decrease of its availability. Accordingly, the obtained monetary values represent the preferences of each person, and by extension, of the whole society.

The monetary values are evaluated by means of two different approaches [6]:

- WTP: amount of money that stakeholders would spend in order to gain a certain benefit;
- WTA: amount of money that stakeholders would spend in order to avoid a certain negative impact;

If the good under estimation is tangible and it belongs to a near perfect market, then the monetary value obtained by those approaches reliably represents the stakeholders' preference. On the contrary, if the perfect market condition is far, the estimated value has to be adjusted.

Intangible effects are costs and benefits which involve, for example, environmental, social and health impacts. Since intangible effects do not have a market, the monetary value is assessable by means of two different classes of methods [2]:

- **Indirect methods**: WTP and WTA are obtained by assessing the behaviour of the individuals;
- **Direct methods**: WTP and WTA are estimated directly from individuals by means of surveys and market simulation such as bidding games.

The Hedonic Price is an indirect method that estimates the preference of the stakeholders on a certain intangible aspect by analysing the market of tangible goods. To illustrate, the monetary value of the environmental impact can be estimated by analysing the real estate market [6]. Among the direct methods class, the Stated Preference techniques involve a direct survey concerning explicitly the good under analysis.

The intangible benefit monetisation techniques are one of the main flaws of the CBA; moreover, both direct and indirect methods are highly time and resource consuming.

Alongside direct and indirect methods, Benefit Transfer is a monetisation technique that inherits the monetary values from similar analyses [7]. Benefit Transfer reduces the resources for evaluating the monetary values of intangible impacts, but its practicability depends on the kind of impact under analysis [3].

Externalities related to a project are treated similarly to intangible impacts. Externalities describe those impacts in which a part is subjected to effects without pay for the gained benefit, or without receiving any compensation for the incurred costs [2].

2.1.3 Discounting and discount rate

Generally, the wide time horizon of investment options embraces instants in which the currency value is different. In order to compare impacts that occur at different time, their effects are converted to the current monetary value on the basis of the discount rate value [2]. Typically, the discount rate is positive hence a future amount of money decreases its value when discounted. Generally, government bodies provide the discount rate value to be used in the different sectors.

Discounting of future benefits is also related to the "Consumer impatience". According to behavioural studies, individuals prefer immediate benefits rather than future benefit enjoyments [8].

2.2 Strengthens of CBA

CBA is a multidisciplinary approach since heterogenous area of interest can be considered simultaneously (e.g., economy, society, scientific, technical). The assessment of an investment option can be undertaken at different stages of the investment life cycle: CBA "ex-ante", CBA "on progress", and "CBA ex-post" [9]. At the planning stage, the goal of a CBA "ex-ante" is to evaluate the economic feasibility of different investment options. CBA "on progress" appraises the performance of the deployed investment option to assess ameliorative changes, while the CBA "ex-post" is made at end of the project time horizon for collecting data useful for future planning processes. Furthermore, CBA is an incremental approach which allows to directly compare different options. In general, the expected outcomes of each investment option are referred to a common baseline scenario devised as Business As Usual (BAU) projection of the current state [9].

Main characteristics of CBA are: efficiency, objectivity, and transparency [3]. CBA is oriented to the maximum spending efficiency, in fact, it highlights the investment option that maximises the profits. According to its advocates, the result provided by a CBA is objective because none of the stakeholders is intentionally favoured or penalised by the assessment process. Moreover, costs and benefits expressed in monetary terms are easy to compare also for non-expert stakeholders, it ensures transparency at the CBA.

2.3 Drawbacks of CBA on the public investment assessment

CBA framework has been devised for assessing the investments in the private sector. Since CBA fundamentals rely on market paradigms, the investment appraisal of the public sectors shows some underlying shortcomings [3]. The private and public sector have three key differences that make the CBA unsound for the latter. Firstly, public policies involve goods and services which are not tradable. Secondly, the goal of the public sector lies on the maximisation of the expense efficiency while the private sector aims at maximizing the profit. In conclusion, the societal point of view modelled as an aggregated consumer behaviour neglects the real values of people as citizens. These shortcomings are emphasised if intangible impacts are non-negligible, hence the result provided by CBA can be misleading [3]. Since intangible impacts are often majoritarian in the public sector, the necessary adjustments on CBA methodology weaken its validity. In fact, monetising and discounting intangible impacts distort the actual preferences of individuals; for example, long term impacts on environment can be underestimated [3].

2.3.1 Quantification and monetization of intangible impacts

The monetary value obtained for each impact directly depends on the accuracy of its quantification. Therefore, a reliable CBA result is achievable only if each impact is properly quantified. Unlike tangible impacts, the intangible ones are often not clearly quantifiable hence they are frequently neglected in CBAs [3]. In order to preserve the validity of CBA, the approach suggested in [4] concerns a CBA limited only to tangible impacts while intangible impacts are assessed aside. Considering this framework, MCA can be effectively combined with CBA to obtain an overall appraisal of investment options without weakening CBA.

As previously discussed, monetisation techniques are not capable to properly collect the point of view of individuals on intangible impacts such as life, health, and environment. In Literature is shown that the actual values scale on some intangible aspect is different than the value obtained by means of WTP techniques [3]. Since the public-sector policies strongly influence the citizen's sphere, a rough estimation of people's point of view may enhance the focus on economic performances [3]. Furthermore, by considering the citizen preferences as aggregated WTP the value assigned to each impact becomes fixed prior to the analysis.

In conclusion, regardless the accuracy of the monetary value obtained, the amount of resources needed for monetizing intangible benefits can be non-sustainable with respect to the expected effort for conducting the whole CBA.

2.3.2 Discounting of intangible impacts

Despite its validity in the financial sector, discounting of intangible impacts appears unsound because it leads to an increased burden on future generations [3]. In fact, the discounting practice lowers the future monetary values, thus the relevance of future benefits and costs with respect to present impacts is underestimated. Namely, the discounting approach makes long term impacts less important than the mid/short terms ones even if the order of magnitude among them is comparable. To overcome this drawback, the use of lower discount rate for intangible impacts is suggested [3]. Accordingly, it distorts the CBA methodology and also lowers the profitability of the considered investment option. Because of its pitfalls, the usage of the discounting technique is discouraged on sectors in which the extent of the negative consequences increases along the delay of corrective actions (e.g., environmental and health sector) [3].

2.3.3 Objectivity, transparency, and equity

The objectivity of the CBA on public sector is no longer ensured due to the underlying hypotheses needed to quantify, monetize, and discount intangible impacts [3].

According to CBA detractors, the complexity of the CBA process precludes a non-expert participation. In addition, the use of currency as a common unit of measurement for impacts moves the focus from the matter of the planning process to the economic performances [3], [6].

Since the values scale of stakeholders is modelled according to market paradigms, the equity shown on financial analyses is no longer insured on social analyses. In general, the monetary values of WTP and WTA are higher for richer communities, the risk of an increased burden of negative impacts on poor communities is real. [3]. Namely, poor communities may seem more accommodating with respect to negative impacts generated by the investment options. This estimation may lead to inequalities among communities which have different wealth levels.

3 Multi-Criteria Analysis

3.1 Introduction on Multi-Criteria Decision-Making and decision support

Multi-Criteria Decision Analysis (MCDA), or MCA, encompasses several decision-making tools useful for identifying the best option among a set of feasible alternatives. The MCA purpose is to help the Decision Maker (DM) in the decision-making process rather than to directly provide the final decision [6]. In fact, MCA decomposes the complex decision-making problem in several elementary problems which are easier managed by DMs. The alternatives of the given set are appraised on the basis of their performances on several conflicting criteria. Moreover, the coexistence of different criteria allows for a simultaneous evaluation of tangible and intangible impacts. Plenty of MCA methods have been proposed in Literature, differences are related both to the underlying decision-making philosophy and the employed mathematical approach. As a consequence, it is not ensured that different MCA methods provide the same outcome even if exploited on the same decision-making problem [10]. Basically, MCA is composed of two main group of methods: Multi-Objective Decision Making (MODM) and Multi-Attribute Decision-Making (MADM) [11]. MODM methods face continuous multi-criteria problems where the number of alternatives is not explicitly known. The MODM mathematical algorithms design a set of optimal solutions that minimise the objectives along satisfying a set of constraints. Conversely, MADM methods are suitable for multi-criteria decision problems whose goal is to find the best alternative among an explicitly known set. Similar to MODM, MADM problems involve multiple conflicting criteria that define the space where the alternative options have to be analysed. Generally, MADM methods model the DM and stakeholder's point of view by means of weights that reflect the relative importance among the evaluation criteria.

As can be seen in Text Box 1, the fundamental steps of a MADM process correspond with a fully structured decision-making process [6].

Text Box 1. Steps of a MADM process [6]

1. **Establish the decision context.**
   A. Establish aims of the MCDA, identify decision makers and other key players.
   B. Design the socio-technical system for conducting the MCDA.
   C. Consider the context of the appraisal.
2. **Identify the options to be appraised.**
3. **Identify objectives and criteria.**
   A. Identify criteria for assessing the consequences of each option.
   B. Organise the criteria in a hierarchy.
4. **'Scoring'. Assess the expected performance of each option against the criteria. Then assess the value associated with the consequences of each option for each criterion.**
   A. Describe the consequences of the options.
   B. Score the options on the criteria.
   C. Check the consistency of the scores on each criterion.
5. **'Weighting'. Assign weights for each of the criterion to reflect their relative importance to the decision.**
6. **Combine the weights and scores for each option to derive an overall value.**
   A. Calculate overall weighted scores at each level in the hierarchy.
   B. Calculate overall weighted scores.
7. **Examine the results.**
8. **Sensitivity analysis.**
   A. Do other preferences or weights affect the overall ordering of the options?
   B. Look at the advantage and disadvantages of selected options, and compare pairs of options.
   C. Create possible new options that might be better than those originally considered.
   D. Repeat the above steps until a 'requisite' model is obtained.

3.2 Key features of MADM Methods

In MADM stakeholders play an important role during the whole evaluation process. In fact, the final goal, the evaluation criteria, their relative importance, and the measure of the option performances strongly depend on the stakeholder's preferences. Accordingly, a certain degree of subjectivity is intrinsic in the MADM outcome [6]. In general, the MADM deals both subjective judgments and objective data to appraise the extent to which each alternative meets the main goal. Therefore, the MADM requires defining measurable criteria, the performances of the alternatives can be expressed in quantitative or qualitative terms.

Unlike CBA, there is no explicit need to define a rule which states that benefits must exceed costs. Therefore, the best option indicated by MADM may not fit the principle of the improvement of the well-being, namely the "doing nothing" principle might result as preferable [6]. In order to avoid this behaviour, the final goal and the criteria have to be carefully defined.

3.3 Common features among MADM techniques

3.3.1 Performance Matrix

The Performance Matrix (PM) constitutes the input of MADM techniques since its elements are the performances of the alternatives with respect to each evaluation criteria. For example, each row of the PM describes an option of the set under analysis while each column is related to an evaluation criterion. The performances stored in the PM related to different criteria can be expressed by means of different unit of measurements [6].

In fully structured MADM methods, the PM is provided as input to an algorithm that systematically converts and processes the data in order to provide as output a comprehensive and synthetic information about the worthiness of each option.

3.3.2 The scoring stage

Typically, MCA techniques involve a scoring stage of the performances stored in the PM. The measured impacts are converted to a common normalised numerical scale. To illustrate, a greater score will be assigned to the alternative that better satisfies the considered criterion.

3.3.3 The weighting stage

In MADM analysis the preferences of the stakeholders are used to define the relative importance of the evaluation criteria. Accordingly, during the weighting process, a numerical value is assigned to each criterion as a relative weight. The point view of stakeholders can be gathered in several ways. Different stakeholders' points of view can be modelled by different patterns of weights. Then multiple MADM analysis can be made to assess the robustness of the obtained result with respect to different scenarios [12].

The weighting stage is crucial for the reliability of the MADM analysis, several techniques for collecting preferences and assigning relative weights have been proposed in Literature. In general, the stakeholders' point of view is reliably represented by criteria weights if preferences are collected from properly informed individuals.

3.3.4 The computation algorithm

Each MADM technique can be considered as an algorithm that combines scores and weights in order to compute an overall score that measures the global worthiness of each alternative with respect to the goal of the decision-making problem. As previously described, the PM and the weights of the criteria are the inputs of the algorithm.

The MADM technique has to be chosen according to the characteristics of the decision-making problem under analysis. Generally, is preferable the use of a simple MADM technique in order to preserve the DM's control on the decision-making process [7].

3.4 MADM methods classification

Due to the great diversity of real decision problems, a large number of MADM methods have been proposed in Literature. This multiplicity allows the DM to find the MADM method that best fit to the decision problem.

In general, MADM methods can be classified according to their approach in three main families [13]:

- Full aggregation approach (FAA);
- Outranking approach (OA);
- Goal, aspiration or reference level approach (GAA).

FAA methods provide as output a complete ranking with score of the alternatives; in addition, FAA methods are compensative methods (low scores on some criteria can be compensated by high scores on the remaining). Most of FAA methods are based on a linear additive combination, among the weights of criteria and performances. The *analytic hierarchy process* (AHP), the *multi-attribute utility theory* (MAUT), and the *measuring attractiveness by a categorical-based evaluation technique* (MACBET) are several methods of the FAA family. OA methods are based on the concept of outranking; accordingly, the aim of these methodologies is to find the set of alternatives which dominate the remaining. The binary relationships of dominance among alternatives are evaluated by means of a pairwise comparison process that involves performances on criteria and their relative weights. The OA methods do not allow compensation among criteria. The most common OA methods are *elimination et choix traduisant la realité* (ELECTRE methods) and *preference ranking organization method for enrichment evaluation* (PROMETHEE). Finally, the GAA family is based on the distance measured between each alternative and an ideal option that can identify the ideal best or worst solution. The *technique of order preference similarity to the ideal solution* (TOPSIS) belongs to the GAA family.

The basic formulation of MADM methods is suitable for exact decision processes. With the aim of undertaking the uncertainty that usually influences real decision-making problems, several modified MADM methods have been proposed in Literature [6].

4 Description of some MADM methods

4.1 Scoring and Weighting techniques

In general, the scoring and the weighting stage are the procedural pillars of each MADM technique. On one hand, in Literature is possible to find fully structured methods that encompass the whole MCDM process. On the other hand, several scoring and weighing standalone processes have been devised to fit the MCA characteristics to each particular decision-making problem.

4.1.1 Scoring techniques

Since the performances on different criteria are measured by means of different unit of measurement, the elements of the PM have to be converted to a common numerical scale. In general, the performances are scaled towards a fixed range numerical scale. The scaling function has to be monotonic, the assigned score has to increase along with the criterion satisfaction. Namely, higher performances have to be related to greater scores.

In general, the reference points of the scaling interval are defined according to the following approaches [6]:

- **Local Scaling:** for each criterion, the maximum and the minimum value of score scale are related to the highest and to the lowest value of performance observed in the PM.
- **Global Scaling:** for each criterion, the extreme values of the score scale are related to performance values arbitrarily chosen.

The global scaling is preferable when it is likely to further consider new options that have performances outside the range of the pre-existing options.

Once the performance range is defined, the scores can be computed according to three approaches [6]:

- Scaling Function;
  - Linear increasing function;
  - Linear decreasing function;
  - Non-linear function;
- Direct Rating based on subjective judgement;
- Rating based on pairwise comparison of the alternatives.

4.1.2 Weighting techniques

The weighting techniques are tools useful for collecting the stakeholders' preference and compute the relative weights of criteria.

4.1.2.1 Trade-off Method

The Trade-off method is based on the pairwise comparison of criteria [14]. For each pair of criteria, two artificial alternatives that differ only in the performance level of those criteria are built. First, the stakeholders have to choose one of this two alternatives; then, their willingness to give up on one criterion to improve the other one is assessed. The behaviour of the stakeholders defines the trade-off weights between criteria. Drawbacks of the Trade-off method are its complexity and the high degree of inconsistency on collected preferences. In addition, the computational effort increases along with the number of criteria since the number of pairwise comparisons required grows.

4.1.2.2 Swing Method

The Swing method is based on the analysis made by the stakeholders of two artificial options: the option W that has the worst level of performances on all criteria, and the option B that has the best level of performances on all criteria [14]. The relative weights of criteria are obtained by an iterative process in which stakeholders have to decide which performance level of W swing to B level. The importance of criteria is related to the chronological order of this choices. In comparison to Trade-off method, Swing method is easier and less sensitive on inconsistencies of preferences. Moreover, the number of criteria less influences its computational effort.

4.1.2.3 Resistance to Change Method

Resistance to Change method is mainly used for the preference elicitation on outranking methods [14]. Resistance to Change method introduces elements of the Swing method within a criteria pairwise comparison framework.

4.2 The Analytic Hierarchy Process (AHP)

4.2.1 Introduction

The Analytic Hierarchy Process (AHP) has been proposed by Thomas L. Saaty in the mid ‘70s [15]. Regardless some theoretical criticism, AHP has been employed to solve decision-making problems in various sectors [6]. AHP is a fully-structured method which handles simultaneously quantitative and qualitative input data. Key features of AHP are the hierarchical decomposition of the decision problem, the ratio scale used for express preferences, and the pairwise comparison procedure. The scoring and weighing stages are addressed by the pairwise comparison of the considering objects. In general, the comparison depends on the personal judgments of the DM that defines the relative importance of one object over another. This evaluation is quantified on a standardized judgment scale (Saaty’s ratio scale) that converts the preferences expressed in verbal terms to a numerical value. Scores and weights are aggregated by means of a linear additive relation, hence an overall worthiness score is assigned to each alternative. Accordingly, the appraised alternatives are ranked, the best alternative of the analysed set is the one that achieves the highest overall score.

4.2.2 Procedural steps of AHP

The AHP methodology can be summarised in 4 procedural steps.

1. **Modelling of the decision-making problem**

The set of the alternatives under analysis, the evaluation criteria, and their hierarchical structure has to be defined. Moreover, the PM has to be built.

2. Scoring and Weighting stages

Even if scoring and weighting stages are two distinct phases of the AHP, the procedure used to determine weights and scores is exactly the same. In the scoring stage, a preference matrix of the alternatives is obtained for each terminal criterion. In the weighting stage, a preference matrix of the criteria is computed for every criterion of the upper level. For each terminal criterion, the preference matrix of the alternatives contains as entries the judgments of the DM expressed in terms of the Saaty's ratio scale. Similarly, by using a pairwise comparison process the weights of criteria are evaluated according to their relative importance in order to fulfill parent criterion. For each hierarchical level, a preference matrix of criteria is obtained for each branch of the overall hierarchy. In classical AHP, the subjectivity of the DM influences both the scoring and weighting stage. In the scoring stage, the DM expresses the preference about the alternatives taking into account their performances on the evaluation criterion. Similarly, the relative weight of each criterion is established in the weighting stage. The preferences of the stakeholders are expressed in verbal terms and then converted to the Saaty's ratio scale (Table 1). The intermediate integer values (2, 4, 6, 8) can be used to express a preference between two adjacent judgments.

Table 1. Saaty's judgment scale [15]

Verbal judgement	Saaty's ratio scale (w_j / w_k)
Absolute preference for object w_k	1/9
Demonstrated preference for object w_k	1/7
Strong preference for object w_k	1/5
Weak preference for object w_k	1/3
Indifference/equal preference	1
Weak preference for object w_j	3
Strong preference for object w_j	5
Demonstrated preference for object w_j	7
Absolute preference for object w_j	9

The number of required pairwise comparisons for AHP increases as the number of the criteria and/or of the alternatives increase. The DM is assumed coherent in his judgments about each pair of objects. Therefore, the elements of lower triangle of a preference matrix are the reciprocal of the corresponding elements of the upper triangle (i.e., $q_{i,j}^{(k)} = 1/q_{j,i}^{(k)}$). In addition, the entries of the main diagonal are equal to 1. To illustrate, Table 2 depicts an example of a preference matrix.

Table 2. AHP preference matrix example

	A	B	C
A	1	7	9
B	1/7	1	2
C	1/9	1/2	1

3. Consistency check and priorities computation

Even if the consistency of judgment within a pairwise comparison is assured, the consistency of the DM preferences about the whole set of objects in the preference matrix is not guaranteed. Therefore, it is imperative to check the consistency level in the preference matrix. The traditional method for checking consistency is based on the evaluation of a consistency ratio (CR) which has to be compared to a threshold value (e.g., $CR^{threshold}= 0{,}1$) [16]. Conversely, the consistency of large matrices is checked by means of statistical approaches [17]. Once a consistent preference matrix is obtained, the corresponding priorities are evaluated. The priorities related to a preference matrix of the scoring stage represent the normalized score of each alternative with respect to the considered criterion. Conversely, the priorities related to a preference matrix of the weighing stage are the normalized local weights of the criteria involved. Priorities from preference matrices can be evaluated by using different approaches; the classical one establishes that the priorities are equal to the normalized eigenvector of the maximum eigenvalue of the preference matrix. If the decision-making problem is not flat (i.e., more than one level of criteria exists), the priorities obtained from a preference matrix of criteria are considered as local priorities. The global priorities are evaluated by means of the hierarchical composition principle.

4. Computation of the overall score

The output provided by the AHP is a complete ranking of the alternatives that is obtained by the linear combination of the alternative priorities with global priorities of terminal criteria. The alternative that achieves the highest overall score is the one that the AHP indicates as the best alternative of the analysed set.

4.2.3 Strengths of AHP

Main strengths of AHP are [6]:

- AHP can simultaneously handle input data expressed in quantitative and qualitative terms;
- Its structured approach allows to face complex decision-making problems;
- The reliability of the pairwise comparison process for scoring and weighting is widely recognized;

4.2.4 Weaknesses of AHP

Despite its success, the scientific Literature is still critical towards the theoretical pillars of AHP. According to AHP detractors, the main weakness of AHP are [6]:

- Absence of a clear theoretical foundation between the Saaty's verbal scale and the Saaty's ratio scale;
- Potential internal inconsistency of the Saaty's ratio scale (i.e., if A/B→3 and B/C→5 then A/C→15 that is greater than 9, the maximum value allowed by the Saaty's scale)
- Weights of criteria are obtained independently with respect to the actual level of the performances of the alternatives under analysis. Hence, the DM's preferences on criteria can be biased.

- The final rank of the alternative can change if new alternatives are introduced or some alternative of the appraised set is removed. The rank reversal problem is felt as the most alarming one although Saaty considers it acceptable [18].

4.2.5 MADM techniques originated from AHP.

In Literature, several adjustments on the AHP have been proposed in order to outclass its shortcomings while preserving its strengths [6]. One of the main changes on AHP concerns the evaluation of priorities based on the normalized geometric mean of the preference matrix rows. Furthermore, with the aim to avoid rank reversal problems, the Ratio Estimation in Magnitudes or deci-Bells to Rate Alternatives which are Non- DominaTed (REMBRANDT method) has been devised [19], [20]. In particular, the REMBRANDT method:

- Substitute the Saaty's ratio scale by a logarithmic scale;
- Uses the geometric mean method for computing priorities.

In conclusion, AHP assumes that criteria are mutually independent, to face decision-making problems with dependence and feedbacks among criteria the Analytic Network Process (ANP) has been proposed by Saaty [21].

4.3 MAUT Methods

4.3.1 Introduction

The MAUT methods family is mainly adopted in the Anglo-Saxon countries and its main feature is the *utility function U* which models the DMs' preferences [13]. The underlying hypothesis relies on the fact that DMs tend to optimise a function which aggregates his own preferences; this behaviour may be conscious or not. Moreover, at the beginning of the decision-making process the utility function may be unknown, hence MAUT methods require to build it.

Generally, MAUT methods manage quantitative information on performances and criteria relevance. Nevertheless, qualitative information can be treated if previously converted to a normalised quantitative scale. In fact, qualitative data implicitly describe quantitative data classes [7].

MAUT methods require a scoring stage of the PM and a weighting stage for assessing the criteria weights. In general, the methods of the MAUT family involve the following steps:

- Verifying the mutual independence of the evaluation criteria;
- Determining the parameters of the *utility function U.*

By means of the *utility function U* the extent to which each alternative is attractive to the DM is evaluated. The attractiveness is measured by means of the *utility score* that represents the well-being that the alternatives gives to the DM. The global *utility score (US)* of each alternative is evaluated by aggregating the *marginal utility scores* (MUS) obtained on each evaluation criteria [13].

A worthiness ranking of the alternatives is devised on the basis of the preference and indifference relationships ruled by the values of US [13]:

$$\forall\, a, b\ \in A{:}\, a\boldsymbol{P}b\ \Leftrightarrow U(a) > U(b){:}\, a\ is\ preferred\ to\ b$$

$$\forall\, a, b\ \in A{:}\, a\boldsymbol{I}b\ \Leftrightarrow U(a) = U(b){:}\, a\ and\ b\ are\ indifferent$$

Where:
A: is the set of the alternatives under analysis;
$U(a)$: is the US of the alternative a;
$U(b)$: is the US of the alternative b;

Incomparability among alternative is not allowed because the numeric values of the USs are always comparable. Moreover, the preference relation is transitive among alternatives.

4.3.2 Linear Additive Model

The Linear Additive Model (LAM) is the simpler way to define the *utility function U*, it involves a linear relationship among performance scores and criteria weights [7]. The LAM requires decision-making problems with certainty and mutual independent criteria. In general, a pair of criteria is mutually independent if the performance score on one criterion can be assigned without any knowledge about the performance score on the other criterion [6].

A scaling process of the PM is made by converting the performances ($f_i(a)$) in terms of MUS ($U_j(f_i(a_i))$). Next, the MUSs related to different criteria are aggregated by means of a weighted sum (1), in order to evaluate the global utility score of the alternative $U(a_i)$ [13]:

$$a_i \in A{:}\, U(a_i) = \sum_{j=1}^{q} U_j(f_j(a_i)) \cdot w_j \tag{1}$$

Where:
$f_i(a_i)$: represents the performance of the i-th alternative on the j-th criterion;
w_j: is the relative weight of the j-th criterion;
q: is the number of the evaluation criteria;
$U_j(f_j) > 0$ is the j-th marginal utility function.

Usually the marginal utility functions are non-decreasing; on each criterion, the MUS value 1 is assigned to the best alternative. Conversely, the 0 value of MUS is assigned to the worst alternative. Therefore, if the sum of all criteria weights is equal to one, the US of each alternative fall on the 0-1 range.

The shape of each marginal utility function depends on the risk attitude of the DM [13]:

- Concave functions are related to the risk-averse attitudes.
- Convex functions are related to the risk-prone attitudes.

Concave functions are therefore assigned to criteria in which a small difference on low values of performance matters. Conversely, convex functions are assigned to those criteria in which a small difference on high values of performance matters. The shape of the marginal utility functions can be determined by collecting preferences by means of the direct or the indirect methods.

A drawback of LAM is the high share of information required for building the marginal utility functions. OA methods have been devised in order to overcome this drawback; OA fundamentals combine the MAUT principles with the outranking dominance relationship [13].

A special case of LAM is the weighted sum of the scored performances on the evaluation criteria. In this case, the marginal utility functions are modeled as linear functions, the utility score of an alternative i-th is evaluable by means of (2) [13].

$$\forall a_i \in A: U(a_i) = \sum_{j=1}^{q} f_i(a_i) \cdot w_j \quad (2)$$

4.4 Outranking Approach Methods

4.4.1 Introduction

The OA methods are based on the outranking concept: “Option A outranks Option B if, given what is understood of the decision maker’s preferences, the quality of the evaluation of the options and the context of the problem, there are enough arguments to decide that A is at least as good as B, while there is no overwhelming reason to refute that statement” [6], [22]. In OA methods, the alternatives are pairwise compared in terms of their performances in order to define the outranking binary relation. Weights of criteria influence the dominance relation within each pair. Unlike FAA methods, the OA methods are not compensative i.e., in the overall assessment of an alternative, good performances on some criteria cannot counterbalance poor performances on other criteria. Thanks to this feature, OA methods capture the real decision-making behaviour related to the rejection of the alternatives that show an intolerable level of performances on some criteria [6]. Furthermore, OA methods allow the incomparability of the alternatives if the outranking relation is undefinable because of missing data [14]. Conversely, indifference exists when two alternatives are equally good and therefore no one dominates the other. In general, the output provided by outranking methods is the set of dominating options identified by analysing the outranking relationships of the given set of alternatives. The OA has been proposed by Roy in mid '60s and it has obtained a wide diffusion in continental Europe [6], [13]. Despite its advantages, the complexity of outranking methods limits their wider application [6].

4.4.2 MCA based on OA methods

In general, the MCA based on OA methods starts from the PM. Therefore, options, criteria, performances, and weights of criteria have to be already defined according to the MCA principles. In addition, criteria have to be mutually independent. OA methods have been initially devised to face flat decision-making problems, although methods for appraising hierarchical structures of criteria have been devised in recent years [23]. Each OA method involves the pairwise comparison of the alternatives with the aim to define the outranking relationships and identify the dominating set. The differences among OA methods lie on the particular methodology used for addressing these steps. Commonly, an option outranks another if has higher performances on the most relevant criteria, while on the remaining criteria it has not significantly worse performances. Therefore, weights measure the extent to which each criterion influences the outranking relationships between options [14].

4.4.3 The ELECTRE Methods

Among the OAs, the family of ELECTRE methods is one of the main branches [13]. Since the first version presented by Roy in [24], several evolved versions of the ELECTRE method have been proposed. Each new version has been devised with the aim to outclass drawbacks and to adjust the methodology to specific decision-making problem characteristics. Despite the high complexity, ELECTRE methods have been employed in several sectors e.g., environmental, agriculture, water management, energy, finance, transportation, and military [13].

In general, for an effective usage of the ELECRE methods the decision-making problem has to satisfy at least one of the following conditions [25]:

1. The number of criteria is equal or greater than 3;
2. The performances are evaluated by means of ordinal or interval scales;
3. The performances on criteria are measured in terms heterogeneous indices;
4. The compensation of performances is not acceptable for the DM;
5. The decision-making problem requires the use of indifference and preference thresholds on the difference of performances.

Since the performances are handled by means of an interval scale, the scoring stage is not required on ELECTRE methods.

In general, the operators used to describe the binary relation between each pair of alternatives are:

- *S:* outranking operator (i.e., *aSb: a* is at least as good as *b*);
- *P:* strictly preference operator (i.e., *aPb: a* is strictly preferred to *b*);
- *I:* indifference operator (i.e., *aIb: a* is indifferent to *b*);
- *R:* incomparability operator (i.e., *aRb: a* is incomparable to *b*).

The possible binary relations among each pair of alternatives are four [25]:

1. *aSb* and *not bSa* (hence *aPb*): *a* outranks *b*;
2. *bSa* and *not aSb* (hence b*Pa*): *b* outranks *a*;
3. *aSb* and *bSa* (hence *aIb*);
4. *not aSb* and *not bSa* (hence *aRb*).

The outranking relation (*aSb*) between each pair of alternatives is not transitive, it can be crisp, fuzzy or embedded, and it is built on the concepts of *Concordance* and *Discordance* of the criteria on the *aSb* statement [25]. *Concordance* exists if a sufficient majority of criteria agree with the dominance relationships while none of the *discordant* criteria strongly disagree on *aSb*.

The dominance relationships can be represented graphically in order to give an easier understanding of the outranking set (Figure 1).

The outranking relationship between two alternatives is defined according to the performances on the evaluation criteria. In addition, the dominance of an alternative on another is influenced by the relative importance of the criteria and the performance difference thresholds.

Considering 3 options: ***a***, ***b***, ***c***.

Outranking relationships:
bSa; ***bSc***; ***cSa***:

The dominant option is ***b;***

b dominates ***a*** and ***c***;

b is not dominated by any of the remaining options.

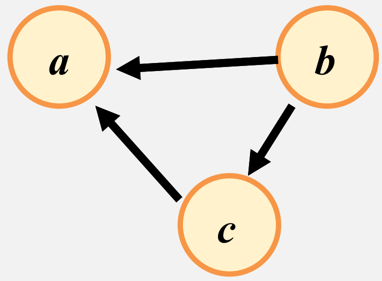


Figure 1. Example of dominance relationships [26]

4.4.3.1 The ELECTRE III Method

ELECTRE III is one of the most acknowledged methods among ELECTRE family, its algorithm is divided into two stages [13]:

1. The computation of the outranking relationships;
2. The exploiting of the obtained outranking relationships.

In the first stage, the DM has to define weights of criteria and the preference, indifference, and veto thresholds. Then, the outranking relationship of each pair of alternative can be built. In the second stage, the outranking relationships are analysed for identifying the dominant set of alternatives.

Key features of the ELECTRE III algorithm are [13]:

- The outranking relationship *aSb*;
- The outranking degree *S(a,b): S(a,b)* measures the credibility of *aSb*. The numerical value of *S(a,b)* is between [0, 1], it approaches to 1 as *aSb* has a higher credibility. The value of *S(a,b)* depends on *concordance* and *discordance* of the criteria to the *aSb* statement.
- The indifference threshold q_i: it is the greatest difference on performances on a criterion that makes two options indifferent for the DM's point of view.
- The preference threshold p_i: it is the smallest performance difference on a criterion that makes an option preferred to the other for the DM's point of view [27].
- The veto threshold v_i: it is the smallest performance difference on a criterion which leads to the rejection of the proposed outranking relationship, albeit the other criteria agrees with it [27].

Indifference, preference, and veto thresholds can be defined as absolute values, or as functions of the values of performances. In general, (3) has to be verified [13].

$$q_i \leq p_i \leq v_i \tag{3}$$

First stage: computation of the dominance degrees

The dominance degree *S(a,b)* is evaluated by means of the concordance and discordance indices ($c_j(a,b)$ and $d_j(a,b)$, respectively). Firstly, those indices are evaluated for each criterion (partial indices), then the global concordance index (*C(a,b)*) is obtained. Finally, the outranking degree *S(a,b)* of the alternative *a* on the alternative *b* is computed by aggregating the discordance indices and the global concordance index.

The partial concordance index cj(a,b) measures the credibility of the outranking relationship *aSb* with respect to the j-th criterion. cj(a,b) is evaluated by means of (4), (5), and (6) [27].

$$c_j(a,b) = 1 \quad if\ f_j(b) - f_j(a) \leq q_j \tag{4}$$

$$c_j(a,b) = \frac{p_j - [f_j(b) - f_j(a)]}{p_j - q_j} \quad if\ q_j < f_j(b) - f_j(a) < p_j \tag{5}$$

$$c_j(a,b) = 0 \quad if\ f_j(b) - f_j(a) \geq p_j \tag{6}$$

The partial discordance index $d_j(a,b)$ measures the degree of discordance on the outranking relationship *aSb* of each criterion. $d_j(a,b)$ is evaluated by means of (7), (8), and (9) [27].

$$d_j(a,b) = 1 \quad if\ f_j(b) - f_j(a) \geq v_j \tag{7}$$

$$d_j(a,b) = \frac{[f_j(b) - f_j(a)] - p_j}{v_j - p_j} \quad if\ p_j < f_j(b) - f_j(a) < v_j \tag{8}$$

$$d_j(a,b) = 0 \quad if\ f_j(b) - f_j(a) \leq p_j \tag{9}$$

The global concordance index *C(a,b)* aggregates the partial concordance indexes obtained for each criterion taking into account the relative weights of criteria. *C(a,b)* is evaluated by means of (10) [27].

$$C(a,b) = \frac{\sum_{j=1}^{q} w_j \cdot c_j(a,b)}{\sum_{j=1}^{q} w_j} \tag{10}$$

Finally, the outranking degree *S(a,b)* aggregates the global concordance index *C(a,b)* and the partial discordance index $d_j(a,b)$. Therefore, *S(a,b)* measures the strength of the outranking relationship *aSb*. *S(a,b)* is evaluated by means of (11) and (12) [27].

$$S(a,b) = C(a,b)\ se\ d_j(a,b) \leq C(a,b)\ \ \forall j \tag{11}$$

otherwise:

$$S(a,b) = C(a,b) \cdot \prod_{V} \left[\frac{1 - d_j(a,b)}{1 - C(a,b)} \right] \tag{12}$$

Where V represents the set of criteria which $d_j(a,b) > C(a,b)$.

In order to avoid that a single criterion would be responsible for the final decision on the outranking relationship when the veto threshold is not exceeded, the *non-dictatorship* condition ((13) has to be respected [27].

$$w_j \leq \sum_{\substack{k=1 \\ k \neq j}}^{q} w_k \tag{13}$$

Second stage: distillation

The second stage of ELECTRE III is called *distillation*, the previously obtained outranking degrees are exploited by two iterative procedures that identify the dominant set. Each iterative procedure provides a partial ranking of the alternatives, the intersection between the partial rankings is the final ranking of the alternative according to the ELECTRE III method [13].

Before the distillation procedure, a worthiness score is assigned to each alternative according to its outranking behaviour. The worthiness score of an alternative is unitarily increased each time it dominates another. Conversely, the worthiness score is unitary decreased each time the alternative is dominated.

In each iteration of the descending distillation procedure, the set with the highest worthiness score is extracted from the whole set of the alternatives under analysis. Therefore, a ranking of the alternatives is built by considering iteratively sets with a decreased value of worthiness score. O_1 is the partial ranking obtained by means of the descending distillation procedure. Similarly, the ascending procedure provides a partial ranking of the alternatives (O_2) built according to the increasing values of the worthiness score. Once the partial rankings O_1 and O_2 are obtained, the intersection between this sets is evaluated. The intersection set is found according to the following global relationships [13]:

- $a\ is\ globally\ better\ than\ b\ (a \succ b), if\ and\ only\ if$:

  a is *better* than *b* in O_1 and O_2, or

  a is *indifferent* to *b* in O_1 but *better* than *b* in O_2, or

  a is *better* than *b* in O_2 and *indifferent* to *b* in O_1.

- $a\ and\ b\ are\ globally\ indifferent\ (a \equiv b), if\ and\ only\ if$:

  a and *b* are *indifferent* in O_1 and O_2.

- $a\ and\ b\ are\ globally\ incomparable\ (a \boxtimes b), if\ and\ only\ if$:

  a is *better* than *b* in O_1 but *b* is *better* than *a* O_2, or *b* is *better* than *a* in O_1 but *a* is *better* than *b* O_2.

- $a\ is\ globally\ worse\ than\ b\ (a \prec b), if\ and\ only\ if$:

  b is *better* than *a* in O_1 e O_2, or

  a is *indifferent* to *b* in O_1 but *b* is *better* than *a* in O_2, or

  b is *better* than *a* in O_2 and *indifferent* to *a* in O_1.

4.4.4 OA methods for qualitative input data

Frequently, decision-making problems involves qualitative judgments both for assessing the criteria relevance and the level of performances of the alternatives. Several MADM methods focused on qualitative data have been proposed in Literature; among the OA methods, REGIME [28] is the one of the most acknowledged. The main feature of REGIME is its capability to accept mixed input data both for alternatives score and criteria weights [26]. According to the OA, REGIME defines the dominance relationships between the alternatives by means of a pairwise comparison process; but REGIME involves an ordinal generalisation of this process [6].

4.5 Fuzzy MADA methods

The use of the fuzzy set theory has been introduced in MCA with the aim to manage the imprecision of the input data of the decision-making problem. However, MCA methods based on fuzzy sets are not widely employed in practice, their use is limited to the academic studies [6]. Fuzzy sets represent qualitative data and preferences by means of membership functions with the aim to model the natural language imprecision [6]. Therefore, the attractiveness of an option can be quantified by means of a fuzzy number between [0, 1]. In fuzzy-MCA methods, performances and weights are expressed and managed in terms of fuzzy numbers, but the methodological framework is inherited from the corresponding MCA technique devised for crisp numbers. On one hand, the strength of MCA fuzzy methods relies on the mathematical modelling of uncertainties of real decision-making problems. On the other hand, the high complexity and the choice of the most reliable membership functions are the main shortcomings [6].

5 Combined use of MCA and CBA

5.1 Introduction

As described in the previous sections, both CBA and MCA evaluate the goodness of investment alternatives. Moreover, both analysing approaches allow a comparative appraisal of the investment options.

CBA shows some fundamental lacks if it is employed on decision-making problems which involve a great share of intangible impacts and/or externalities. If the quota of those elements is considered negligible, a CBA limited to tangible impacts can be addressed. Intangible impacts and externalities can be mentioned alongside the CBA results to provide additional information. Conversely, if intangible impacts and externalities are majoritarian, it is necessary to include them within a structured assessment framework.

MCA involves several criteria that can be mutually conflicting; the main advantage of MCA consists in the fact that it does not require expressing all impacts/benefits in monetary terms; therefore, all intangible impacts and externalities can be effectively assessed. Moreover, MCA outclasses the shortcomings of the monetisation techniques of the CBA by means of a pattern of weights that directly models the stakeholders' preference.

In conclusion, the flexibility of the MCA framework allows to include in the appraisal the result of a rigorous CBA of monetary impacts. Therefore, the structured appraisal of the whole decision-making problem is possible.

5.2 Main differences between CBA and MCA

Table 3 summarised the strengths and weaknesses of MCA and CBA [29].

Table 3. Comparison of MCA and CBA [29]

	CBA	MCA
Strengths	Rigours and rational; Formalised; Transparent; Widely acknowledged; Independent from judgement; Potentially participative; Easy communication of the results;	Flexible; Not strictly formalised; Democratic; Monetisation of impacts is not mandatory; It assures participation and legitimacy;
Weaknesses	Difficult and expensive technique; It needs a large amount of data, often hardly obtainable; Impossible to assess "soft effects"; The equity achieved depends on the DM;	Potentially ambiguous and subjective; Some components of arbitrariness, especially in the perception of public costs vs. private benefits; Double counting; Lack of clarity, consistency, accountability;

5.2.1 The management of preferences

In CBA, the preferences of individuals are collected by means of indirect methods based on market paradigms. Conversely, in MCA stakeholders are involved in the decision-making process. Therefore, the stakeholders' point of view is directly collected and their preferences are explicitly related to the decision-making problem at hand. Accordingly, the preferences collected in MCA are doubly specific because are related to the specific stakeholders involved and to the specific decision-making problem under analysis. As a result, the preferences collected in MCA are a more reliable picture of the stakeholders' point of view than the CBA money values.

In addition, a sensitivity assessment about preferences is difficult in CBA because they are not input parameters of the analysis.

5.2.2 Discounting

Unlike CBA, MCA does not concern the discounting of the future impacts. This gives flexibility to MCA because the relevance of future impacts can be directly collected from stakeholders.

5.2.3 Stakeholders involvement

The role of stakeholders is passive in CBA, contrariwise stakeholders are actively part of the MCA procedure. Moreover, the participation of stakeholders in CBA is limited by the lack of transparency of the monetisation techniques.

In MCA, more than one stakeholder's point of view can be investigated by means of different patterns of weights that can be combined or used for executing distinct MCA.

5.3 Final Considerations

In general, planning activities have a limited budget, therefore, an efficient use of resources is mandatory. In the public sector, it is crucial to identify the investment option that maximises the societal benefits. Moreover, in recent years is raised the need for a novel planning approach that better considers environmental and social impacts [7].

CBA is an acknowledged and reliable tool for a company planning in economic and financial sectors. Conversely, CBA shows some fundamental shortcomings if used in the public sector or in decision-making problems that involve a great share of intangible impacts. In this context, MCA can play a key role by outclassing the drawbacks of CBA. Furthermore, CBA is focused on the expense efficiency while MCA focuses on the expense effectiveness by identifying the best alternative for achieving a particular target [4]. Therefore, the result provided by these tools applied independently on the same decision-making problem is different [4].

Regardless the differences of CBA and MCA, these two assessment approaches are not mutually exclusive, a joint use can be useful with the aim of relieving the respective lacks. Basically, the CBA can be considered as an element of an overlying MCA.

In order to maximise the effectiveness of the joint use, CBA and MCA can interact according to two frameworks [4]:

- the CBA is focused only on tangible impacts while the MCA concerns only intangible impacts;
- first, a MCA is made in order to select a subset of interesting investment options; then the economic viability of each selected option is assessed by means of a CBA.

In general, to avoid misleading results the boundary of the appraisal made by each evaluation tool has to be clearly defined.

The assessment quality is improved since the joint MCA-CBA use ensures a deeper and comprehensive analysis of impacts and priorities related to the decision-making problem. Despite its potential advantages, the joint use MCA-CBA it is not yet widely diffused; in Literature, the joint analysis has been introduced with the aim to [4]:

- outclass the lack of CBA on the stakeholders' preference modelling;
- outclass the lack of MCA on the economic assessment;
- outclass the weaknesses of CBA in the evaluation of the intangible impacts;
- promote an active participation of stakeholders in the decision-making.

6 A MC-CBA methodology for the smart-grid assessment

In this section, a joint methodology MC-CBA is proposed. The methodology has been devised for the assessment of smart grid development alternatives. The assessment has a time horizon which encompasses the whole life-cycle of the project alternative.

The proposed approach relies on the assessment guidelines for smart grid projects developed by the JRC and the Italian Regulator (AEEGSI, Autorità per l'Energia Elettrica, il Gas ed il Sistema Idrico). These fundamentals grant validity to the proposed approach whose scientific novelty is the formalisation of the assessment procedure.

6.1 JRC Guidelines for smart grid project assessment

The European Commission (EC) considers the smart grids as a means to achieve several strategic objectives [30]–[32]:

- *Promote the renewable energy sources, also at micro level;*
- *Enhance the security of the network;*
- *Promote energy efficiency and energy savings;*
- *Increase the active role to consumers in a liberalized energy market.*

The complexity related to the smart grid impacts is acknowledged by the European Union (EU), in fact, the eligibility of design options depends on the result of the evaluation in economic, social, and environmental terms [30]. In accordance with the EC proposals, JRC developed methodological guidelines for conducting a CBA of smart grids assets. The aim is to provide a common appraisal framework for all Member States. The JRC guidelines for conducting a CBA on smart grids assets have to be concerned as [31], [32]:

- *a structured set of suggestions;*
- *a checklist of important elements to consider in the analysis;*

The JRC assessment framework involves [31], [32]:

- a CBA of monetary impacts;
- a qualitative analysis of non-monetary impacts.

Namely, JRC suggests a CBA focused only on tangible impacts, while intangible impacts have to be evaluated aside by means of a qualitative appraisal tool (Figure 2).

The tangible impacts considered have to be related to the whole electric power system and the society, not only the companies directly involved in the smart grid planning option. Therefore, the CBA actually changes into a Social Cost-Benefit Analysis (SCBA).

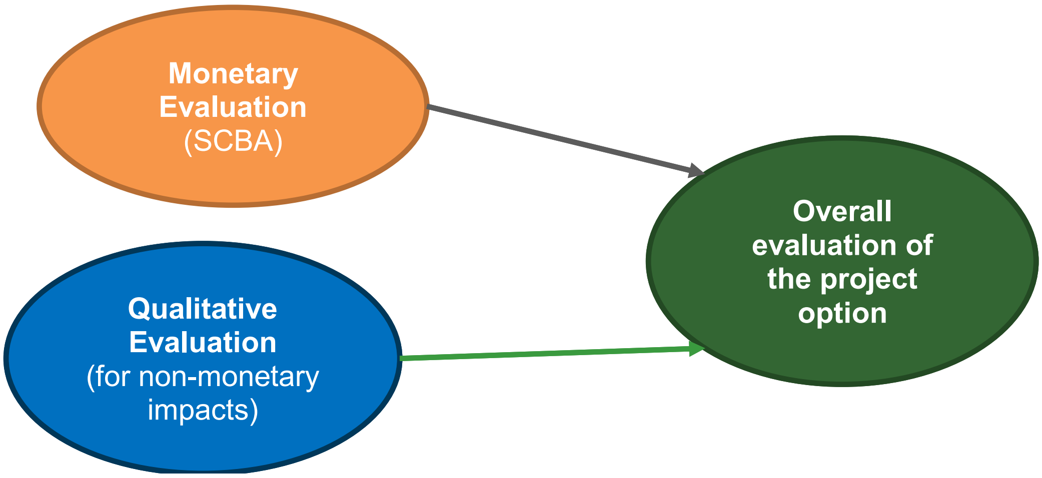


Figure 2. Project option assessment according to JRC

The approach proposed by JRC is mainly focused on the CBA, it aims to provide [31], [32]:

- *support to choose key parameters;*
- *a systematic approach to link assets with benefits;*
- *a possible (non-exhaustive) set of formulae to monetize benefits;*
- *an illustration of a sensitivity analysis to identify critical variables affecting the CBA outcome.*

The outputs provided by the CBA according to the JRC framework are the classical economic indices: NPV, IRR, and CBR.

The JRC guidelines also concern the evaluation of the intangible impacts, that has to be focused on [31], [32]:

- the merit of the project option in terms of the expected outcomes on policy objectives;
- externalities (e.g., new services enabled, job creation, consumer inclusion).

It is also suggested to quantify non-monetary impacts by means of the physical unit of measurements or qualitative indices [31]. By combining quantitative and qualitative indices is possible to evaluate the overall outcome of the qualitative appraisal. In addition, a pattern of weights can be introduced in order to weigh each impact on the basis of its relative importance according to the DM point of view.

6.2 The proposed MCA approach

The JRC assessment framework corroborates the need for a structured evaluation procedure which manages simultaneously both monetary and non-monetary impacts. Therefore, a MCA approach can be suitable. In fact, MCA is a decision-making tool which helps the DM in identifying the best alternative among a given set:

- MCA does not require to express all impact in monetary terms;
- MCA is a structured approach that helps to solve complex decision-making problems.

In the proposed MC-CBA approach (Figure 3), CBA constitutes an input of the overall MCA. As previously argued, the joint use of these evaluation tools guarantees a better analysis of complex decision-making problems that involve a great share of intangible impacts and externalities.

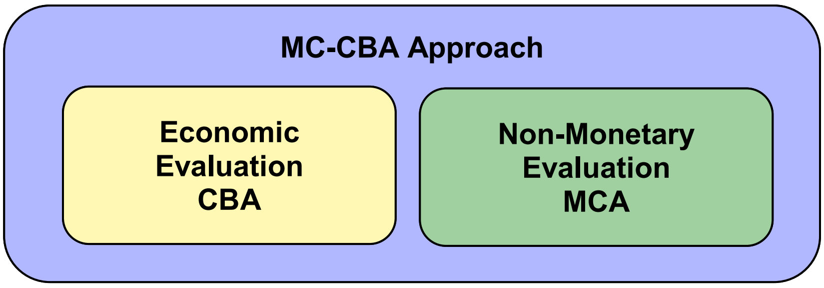


Figure 3. General representation of the MC-CBA model

According to the JRC guidelines, the proposed approach decomposes the decision-making problem by a hierarchical structure. In addition, the concepts of the JRC guidelines are formalised and integrated within a MCA framework. The hierarchical structure of criteria has to reflect the way of achieving the main goal according to the core values of the company (or the organisation) which aims at it. Therefore, each impact has its relative relevance with respect to the main goal that is modelled through criteria weights. Each impact is evaluated qualitatively or quantitatively by means of terminal criteria which are directly measurable objectives. The magnitude of the impacts generated by a project option represents its performances on the evaluation criteria. By combining performances and criteria weights through a MADM technique is possible to obtain the outcome of the MC-CBA framework. As a result, the project option that better satisfies the DM's expectations is identified as the solution of the decision-making problem.

The hierarchical structure is organised according to the principle of abstraction. Therefore, the main goal at the head of the hierarchy is referred to the strategic objectives defined by the EC linked to the vision for the future of the energetic system and the society. The intermediate objectives placed in the first level of the hierarchy represent general goals on specific sectors related to the main goal of the decision problem. The second level hosts criteria which describe specific objectives of the sector which each criterion belongs. The last level of the hierarchy is represented by terminal criteria whose fulfillment is directly measurable by means of the performance indices. The satisfaction of terminal criteria leads to the fulfillment of the criteria of the upper levels of the hierarchy, hence the performances on terminal criteria determine how much a project option contributes to the achievement of the main goal. Therefore, the PM of the decision-making problem is defined by the performances of the project options on terminal criteria.

The proposed approach aims at investigating 3 different area of interest: economic effects, enhanced smartness of the grid, and externalities. The performances of the project options in each area are evaluated by means of a different branch of the hierarchical structure. In Figure 4 an example of generalised PM is depicted where the terminal criteria related to each sector under analysis is highlighted.

	Benefit (1)	...	Benefit (S)	Impact (1)	...	Impact (H)	CBA Index (1)	...	CBA Index (Z)
Alternative 1	Score (1,1)	...	Score (1,S)	Score (1,S+1)	...	Score (1,S+H)	Score (1,S+H+1)	...	Score (1,S+H+Z)
Alternative 2	Score (2,1)	...	Score (2,S)	Score (2,S+1)	...	Score (2,S+H)	Score (2,S+H+1)	...	Score (2,S+H+Z)
...	...	...	...	...	...	...	...	...	...
Alternative R	Score (R,1)	...	Score (R,S)	Score (R,S+1)	...	Score (R,S+H)	Score (R,S+H+1)	...	Score (R,S+H+Z)

Figure 4. Example of Performance Matrix structure

Once the PM is built and weights of criteria are obtained, the best alternative in achieving the main goal can be identified by means of a MADM technique (Figure 5).

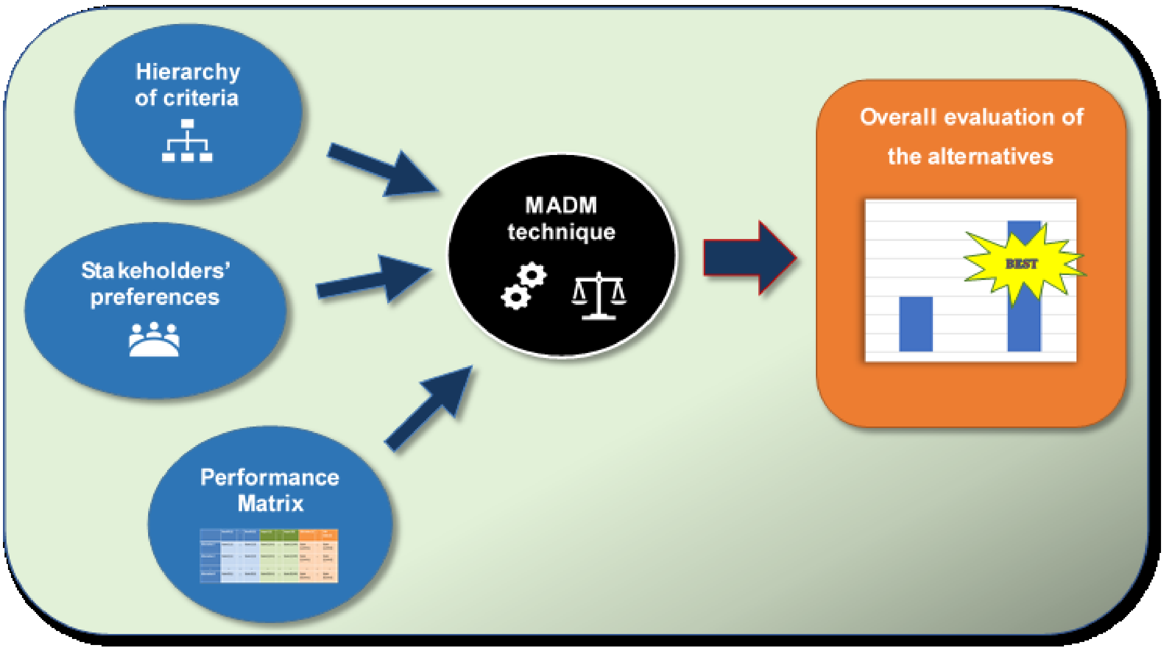
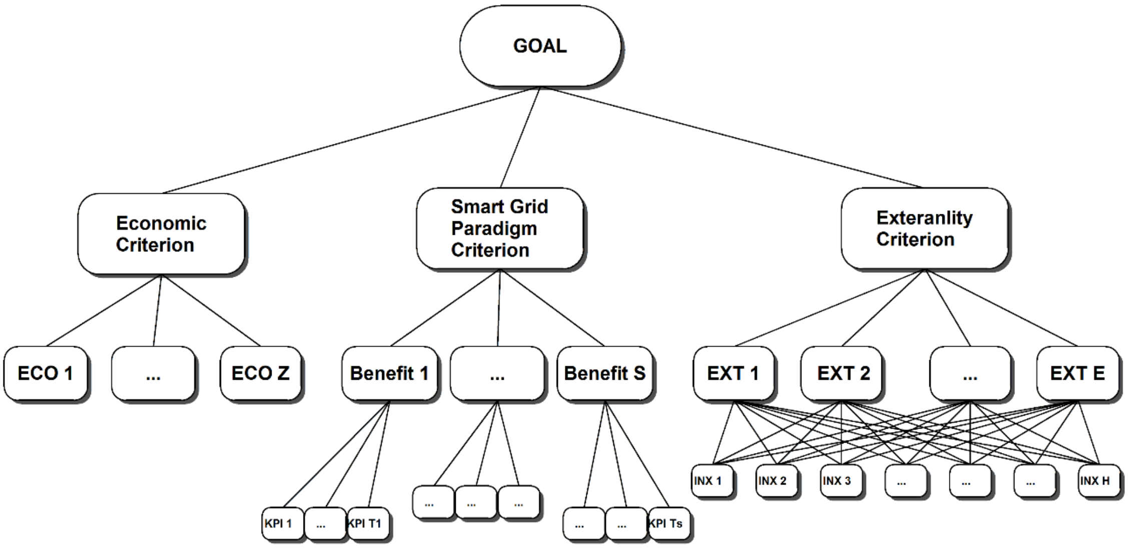


Figure 5. General representation of the MADM assessment framework

6.3 The proposed hierarchical structure for the smart grid assessment

The proposed approach for smart-grid project selection generalises the concepts of JRC guidelines by formalising the decision-making problem according to a MCA framework.

The hierarchical tree of criteria is formed by three independent branches in order to evaluate the impacts of the project options on three areas of interest. Each branch starts from a first level criterion and it is directly linked to the main goal of the hierarchy. Therefore, the overall evaluation of a project options is obtained by combining the result of the evaluation on each branch. The first branch is focused on the economic assessment, the second branch evaluates the contribution towards the smart grid realization, the third branch evaluates the effects of



the project option in terms of externalities (Figure 6). The three branches are independent therefore an impact can be evaluated through its effects on each area of interest. Conversely, each impact has to be considered by means of a single effect on each branch in order to avoid double counting.

Figure 6. Hierarchical structure of criteria for the MC-CB approach

6.3.1 First level criteria

The overall evaluation of the project options is obtained by combining the results of the assessment on the three different branches. Each branch starts from a first level criterion:

- the economic criterion;
- the smart grid deployment merit criterion (smart grid paradigm criterion);
- the externality criterion.

6.3.2 The economic evaluation branch

The economic criterion is the head node of the economic evaluation branch that aims at assessing the economic performance of the project options. The proposed approach involves a CBA of monetary impacts that can be run according to the procedure defined by JRC in [31], [32]. The economic assessment of a project option aims at evaluating its monetary costs and benefits. These economic performances can be represented by means of the indices computed by CBA, or explicitly considering the items of monetary cost and benefits in the tree. In the first case, the economic branch has three criteria in the second hierarchy level (Figure 7).

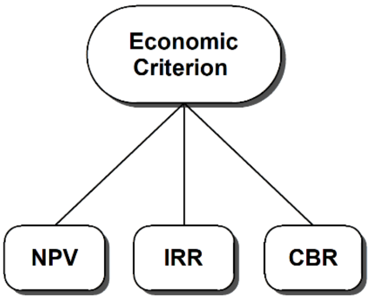


Figure 7. Economic tree based on the CBA output indices

Each criterion is related to a CBA outcome index:

- the NPV criterion measures the project profitability in terms of the net benefit. In general, an investment option is economically viable if NPV is positive. The profitability of the investment increases as the related NPV grows.
- The IRR criterion measures the quality of the investment option. An alternative is positively evaluated if its IRR is higher than the reference social discount rate.
- The CBR criterion measures the efficiency of the investment option. An alternative is positively evaluated if its CBR is greater than one.

Those criteria are fulfilled according to the increasing values of the related indices.

In the second case, the economic branch shows more than one hierarchical level whose criteria are the cost and benefit items related to the project impacts. Figure 8 depicts a

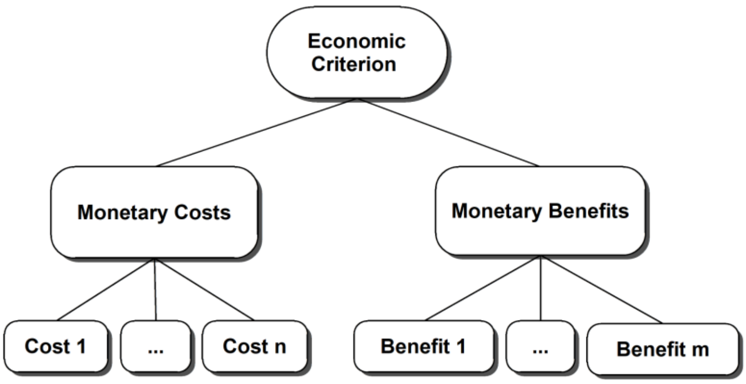


Figure 8. The economic branch with elementary cost and benefits

generalised economic branch with elementary cost and benefits explicitly accounted.

The criteria on the higher hierarchical levels aggregate the elementary monetary criteria of lower levels. In general, two sub-branches can be defined: the cost branch and the benefit branch. The performances on all criteria are measured in terms of currency, therefore criteria are fulfilled by performances that minimise costs and maximise monetary benefits.

6.3.3 The smart grid deployment merit branch

The second branch of the hierarchy tree evaluates the contribution towards the smart grid realization given by the project options. As previously argued, the importance of this evaluation arises from the role of the smart grids in the EU policies.

In [33] the EC defined a list of benefit for the energetic sector related to the smart grid developments. Starting from the EC document, the JRC devised a list of *policy criteria* with the aim to provide common assessment guidelines for smart grid projects [5], [31], [32]. Moreover, the fulfillment of the *policy criteria* is appraised by means of *Key Performance Indicators* (KPIs). The formulas useful for computing most of the KPI have been also proposed by the JRC [5]. Generally, each evaluated KPI is referred to a baseline scenario. It is worth to highlight that the evaluation of the project options through KPI is outcome oriented. In other words, by means of KPIs are not evaluated the technical features of the infrastructure but the effects that it produces.

The structure of the “smart grid paradigm branch” reflects the JRC approach; therefore, the second level criteria are the *policy criteria* while the terminal criteria are the related KPIs. The performances of the project options are measured by means of the KPIs. According to the JRC guidelines, *policy criteria* are mutually independent [5], [31], [32]. Furthermore, KPIs related to a same *policy criterion* have the same relevance [5], [31], [32].

6.3.4 The externality assessment branch

The third branch concerns the assessment of the project options in terms of externalities. With the aim to aggregate single impacts, it is possible to define thematic areas where evaluating the effects under analysis. Single impacts are related to the terminal criteria while the second level criteria are the thematic areas. To illustrate, a thematic area can be the “social area” where a terminal criterion can be the “consumer satisfaction”. Each impact has to be measured by means of a quantitative or qualitative index. Those indices measure the fulfillment of the terminal criteria. Unlike the “smart grid paradigm” branch, it is assumed that the second level criteria are mutually dependent. In fact, an impact related to a thematic area can also influence the other areas.

7 Closing Discussion

In this discussion paper, the need for a new assessment approach for smart grid impacts is highlighted. With the aim to outclass the weakness of the assessment practices currently in use, a combined MC-CBA approach is presented. As discussed in the previous sections, each method has its own advantages; since they are not mutually exclusive, a joint use can be useful with the aim of relieving the respective lacks. The proposed methodology is based on international recommendations on project analysis, as the guidelines released by the JRC. The decision process is broken down into a hierarchy of criteria made of three independent branches: the economic evaluation; the contribution towards the smart grid realization; and the evaluation of externalities. The best alternative is identified according to the DM's point of view on the basis of the monetary and non-monetary impacts assessment.

The proposed methodology provides the assessment of the wide range impacts which a smart grid project option originates. Furthermore, the comparative approach allows to compare several project alternatives with the aim to identifying the best one.

A MC-CBA assessment framework allows decision makers to:

- Assess impacts on different areas of interest;
- Assess monetary and intangible impacts;
- Assess qualitatively non-quantifiable impacts;
- Involve the stakeholders' preferences.

Furthermore, the mixed qualitative-quantitative analysis allows reducing the resources required for the overall assessment, and for including impacts, which are neglected by the CBA.

References

[1] E. J. Mishan and E. Quah. 2007. *Cost-benefit analysis*. Routledge.

[2] S. Momigliano. 2001. *La valutazione dei costi e dei benefici nell'analisi dell'impatto della regolazione.* Rubbettino Editore.

[3] F. Ackerman and L. Heinzerling. 2002. "Pricing the Priceless: Cost-Benefit Analysis of Environmental Protection". *Univ. Pa. Law Rev.*, vol. 150, no. 5, p. 1553.

[4] J. A. Annema, N. Mouter, and J. Razaei. 2015. "Cost-benefit Analysis (CBA), or Multi-criteria Decision-making (MCDM) or Both: Politicians' Perspective in Transport Policy Appraisal". *Transp. Res. Procedia*, vol. 10, pp. 788–797.

[5] V. Giordano, S. Vitiello, and J. Vasiljevska. 2014. "Definition of an assessment framework for projects of common interest in the field of smart grids". *JRC Sci. Policy Rep.*

[6] J. Dodgson, M. Spackman, A. Pearman, and L. Phillips. 2009. *Multi-criteria analysis: a manual*. Department for Communities and Local Government: London.

[7] Risk and Policy Analysts Ltd (RPA). 2004. *Evaluating a multi-criteria analysis (MCA) methodology for application to flood management and coastal defence appraisals Case studies report*. Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme.

[8] A. Pedon and C. Amato. 2009. *Dimmi cosa compri e ti dirò chi sei... Scelte economiche e comportamento d'acquisto*. Armando Editore.

[9] D. Sartori et al.. 2014. *Guide to Cost-Benefit Analysis of Investment Projects. Economic appraisal tool for Cohesion Policy 2014-2020*. European Commission Directorate - General for Regional and Urban policy.

[10] K. T. Cho. 2003. "Multicriteria decision methods: An attempt to evaluate and unify". *Math. Comput. Model.*, vol. 37, no. 9, pp. 1099–1119.

[11] K. Miettinen. 2008. "Introduction to Multiobjective Optimization: Noninteractive Approaches". *Multiobjective Optimization* pp. 1–26. Springer.

[12] S. Kapros, K. Panou, and D. Tsamboulas. 2005. "Multicriteria Approach to the Evaluation of Intermodal Freight Villages". *Transp. Res. Rec. J. Transp. Res. Board*, vol. 1906, pp. 56–63.

[13] A. Ishizaka and P. Nemery. 2013. *Multi-criteria Decision Analysis: Methods and Software*. John Wiley & Sons.

[14] D. Diakoulaki and S. Grafakos. 2004. "Multicriteria analysis". *Eur. Comm. ExternE—Externalities Energy Ext. Account. Framew. Policy Appl.*.

[15] T. L. Saaty. 1977. "A scaling method for priorities in hierarchical structures". *J. Math. Psychol.*, vol. 15, no. 3, pp. 234–281.

[16] B. L. Golden, E. A. Wasil, and P. T. Harker. 1989. *The Analytic Hierarchy Process - Applications and Studies*. Springer.

[17] J. A. Alonso and M. T. Lamata. 2006. "Consistency in the analytic hierarchy process: a new approach", *Int. J. Uncertain. Fuzziness Knowl.-Based Syst.*, vol. 14, no. 04, pp. 445–459.

[18] T. L. Saaty and L. G. Vargas. 1984. "The legitimacy of rank reversal". *Omega,* vol. 12, no. 5, pp. 513–516.

[19] F. A. Lootsma. 1992. "The REMBRANDT system for multi-criteria decision analysis via pairwise comparisons or direct rating". *Reports of the Faculty of Technical Mathematics and Informatics* Vol. 92, Ed. 5.

[20] D. L. Olson, G. Fliedner, and K. Currie. 1995. "Comparison of the REMBRANDT system with analytic hierarchy process", *Eur. J. Oper. Res.*, vol. 82, no. 3, pp. 522–539.

[21] T. L. Saaty. 1996. *Decision making with dependence and feedback: The analytic network process*, vol. 4922. RWS publications Pittsburgh.

[22] B. Roy. 1974. "Critères multiples et modélisation des preéférences (L'apport des relations de surclassement)", *Rev. Déconomie Polit.*, vol. 84, no. 1, pp. 1–44.

[23] S. Corrente, S. Greco, and R. Słowiński. 2013. "Multiple Criteria Hierarchy Process with ELECTRE and PROMETHEE", *Omega,* vol. 41, no. 5, pp. 820–846.

[24] B. Roy. 1968. "Classement et choix en présence de points de vue multiples". *Rev. Fr. Inform. Rech. Opérationnelle*, vol. 2, no. 8, pp. 57–75.

[25] S. Greco, M. Ehrgott, and J. R. Figueira. 2005. *Multiple criteria decision analysis: state of the art surveys.* Springer Science + Business Media.

[26] A. Stratigea and E. Grammatikogiannis. 2012. “A Multicriteria Decision Support Framework For Assessing Alternative Wind Park Locations: The Case Of Tanagra - Boiotia”, *Reg. Sci. Inq.*, vol. IV, no. 1, pp. 105–120.
[27] S. Corrente, J. R. Figueira, S. Greco, and R. Słowiński. 2016. “A robust ranking method extending ELECTRE III to hierarchy of interacting criteria, imprecise weights and stochastic analysis”, *Omega.*
[28] E. Hinloopen, P. Nijkamp, and P. Rietveld.1983. “The Regime Method: A New Multicriteria Technique”. *Essays and Surveys on Multiple Criteria Decision Making* pp. 146–155. Springer.
[29] P. Beria, I. Maltese, and I. Mariotti. 2012. “Multicriteria versus Cost Benefit Analysis: a comparative perspective in the assessment of sustainable mobility”. *Eur. Transp. Res. Rev.*, vol. 4, no. 3, pp. 137–152.
[30] European Commission. 2011. *Smart Grids: From Innovation to Deployment.*
[31] V. Giordano, I. Onyeji, G. Fulli, M. S. Jiménez, and C. Filiou. 2012. “Cost-benefit analysis of Smart Grid projects”. *JRC Sci. Policy Rep.*
[32] V. Giordano, I. Onyeji, G. Fulli, M. Jiménez, and C. Filiou. 2012. “Guidelines for cost benefit analysis of smart metering deployment”. *JRC Sci. Policy Rep.*.
[33] European Commission. 2011. “Proposal for a regulation of the European parliament and of the Council on guidelines for trans-European energy infrastructure and repealing”. *Decision No 1364/2006/EC*.