Benefit-Cost Analyses and Toolkits

MC-CBA toolkit: model and case study

Discussion paer

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ISGAN Annex 3

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Preface

IEA-ISGAN Annex 3 aims 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).

Previous research activities in the context of the Research on the Electrical System and ISGAN have highlighted the shortcomings of a techno-economic assessment based only on a Cost-Benefit Analysis (CBA). Furthermore, the use of hybrid evaluation tools based on Multi-Criteria Analysis (MCA) and CBA has been proposed; a case study referred to the second generation of smart meters has been presented to illustrate the features of the joined assessment. The monetisation of all impacts in not required by a combined MCA-CBA assessment, therefore the flaws related to the techniques for monetising non-monetary impacts are avoided.

The scope of this research is to enhance the integration of CBA (in particular, the toolkits for conducting a simplified CBA developed within the projects PAR 2014 and 2015) and MCA. The combined MC-CBA framework aims at helping the decision maker in identifying the best alternative among a set of different smart grid development options. The proposed assessment methodology has to be automated in order to reject any personal bias and preserve the main interests of stakeholders.

In this document the mathematical model of the MC-CBA framework is described. This framework is exploited by original software, the *MC-CBA toolkit*. This software integrates the CBA within an MCA process. The *MC-CBA toolkit* allows for an output-based assessment of the alternatives based on an automated comparison procedure. To describe the features of the *MC-CBA toolkit*, a case study related to the project selection among different smart grid development plans is presented.

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Nomenclature or List of Acronyms

AHP	Analytic Hierarchy Process
ADN	Active Distribution Network
ANP	Analytic Network Process
BaU	Business as Usual
CBA	Cost-Benefit Analysis
CBR	Cost-Benefit Ratio
DES	Distributed Energy Storage
DG	Distributed Generation
DSO	Distribution System Operator
HV	High Voltage
IRR	Internal Rate of Return
JRC	Joint Research Centre
KPI	Key Performance Indicator
LV	Low Voltage
MCA	Multi-Criteria Analysis
MV	Medium Voltage
NPV	Net Present Value
PC	Policy Criterion
PM	Performance Matrix
SG	Smart grid

Abstract

Nowadays, due to the increasing presence of distributed energy resources and the integration of automation and communication technologies the electric power system is evolving towards the smart grid paradigm. Typically, smart grid projects are responsible of wide range impacts which span from the electrical power system to the entire society. Often, these impacts are not easily quantifiable thus an assessment based on their monetary value is not attainable. In this context, traditional approaches as the cost-benefit analysis (CBA) become unfit. The reliable assessment of several planning options can be obtained by using hybrid approaches which combine monetary appraisal tools within a generalised framework based on multi-criteria analysis (MCA). A combined MC-CBA approach preserves the advantages of each methodology while overcoming the respective weaknesses. This report describes the mathematical model of the MC-CBA framework for smart grid projects proposed in previous research activities. This model is exploited by the original software *MC-CBA toolkit,* which is presented in this document. The *MC-CBA toolkit* aims at supporting the decision makers by providing an assessment framework which rejects any personal bias by preserving the stakeholders' interests. In fact, the *MC-CBA toolkit* allows for an output-based assessment of the smart grid alternatives based on an automated comparison procedure. The *MC-CBA toolkit* decomposes the decision-making problem by dividing the impacts in three main areas: economic impacts, the contribution towards the smart grid realisation, the externality impacts. The calculation procedure for identifying the best option of the set under analysis relies on the Analytic Hierarchy Process (AHP). In order to illustrate the effectiveness of the *MC-CBA toolkit,* a case study focused on project selection among different smart grid development plans is presented. More specifically, a set of different upgrading plans based on the Active Distribution Network (ADN) approach and the siting and sizing of distributed energy storage is analysed. The *MC-CBA toolkit* helps the decision maker to identify the best smart grid investment option; the final aim is to provide a reliable support tool for effectively orienting the investments and the regulatory policies on smart grids.

Executive Summary

Introduction

Nowadays, due to the increasing presence of distributed energy resources and the integration of automation and communication technologies the electric power system is evolving towards the smart grid paradigm. Typically, smart grid projects are responsible of wide range impacts which span from the electrical power system to the entire society. Often, these impacts are not easily quantifiable thus an assessment based on their monetary value is not attainable. In this context, traditional approaches as the cost-benefit analysis (CBA) become unfit. The reliable assessment of several planning options can be obtained by using hybrid approaches which combine monetary appraisal tools within a generalised framework based on multi-criteria analysis (MCA). A combined MC-CBA approach preserves the advantages of each methodology while overcoming the respective weaknesses.

This report describes the fundamentals of the MC-CBA methodology for smart grid project assessment proposed in previous activities for the Research Fund for the Italian Electrical System. The proposed MC-CBA approach is general purpose since it can be used for assessing different smart grid assets. 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 overall goal of the hierarchical tree is to identify the best project option according to the decision maker's (DM) perspective. In order to provide a decision support tool to DMs, an original software which exploits the MC-CBA methodology has been developed, the *MC-CBA toolkit*.

Once the performance metrics of the criteria are defined, the *MC-CBA toolkit* allows for an automatic comparison of the alternatives under analysis. Therefore, the automatized analysis of large sets of feasible project options is possible, while including the stakeholders' point of view and reducing the subjectivity of the appraisal process. The *MC-CBA toolkit* is a decision-making support tool which helps the DM in identifying the planning option that best satisfies the stakeholders' expectations while respecting the economic and financial constraints. With the aim to present the *MC-CBA toolkit,* a case study focused on the decision-making problem of smart grid planning is described in the report.

The model of decision-making in *MC-CBA toolkit*

The combined approach of the *MC-CBA toolkit* is based on the guidelines for smart grid project assessment proposed by the *Joint Research Centre* (JRC). The recommendations of JRC guidelines are generalised and the decision-making problem is addressed according to MCA fundamentals. In the *MC-CBA toolkit* the model of the decision-making problem is obtained by combining three independent evaluations: the economic evaluation (CBA of monetary impacts); the smart grid deployment merit evaluation (MCA of non-monetary impacts); the externality evaluation (MCA of non-monetary impacts). This hierarchical structure of criteria is general purpose for smart grid context; for assessing a smart grid asset, the evaluation criteria have to be carefully chosen in order to obtain an effective assessment and avoid double counting. The structure of criteria is flexible since it can be adapted according to the decision-making problem under analysis. In fact, the *MC-CBA toolkit* allows the end-user to arbitrary define number and type of criteria in each branch.

The Automatized Analytic Hierarchy Process

The algorithm of the *MC-CBA toolkit* is based on the *Analytic Hierarchy Process* (AHP). The AHP technique manages simultaneously quantitative and qualitative information. In general, MCA techniques encompass two main stages: the scoring and the weighting stages. In the former, a normalised score is computed for each alternative according to the performances on each evaluation criteria. In the latter, a weight (or local priority) is assigned to each criterion according to its relevance. AHP is an MCA technique which involves a pairwise comparison process for the scoring and weighting stages. The pairwise comparison collects the preference judgements between objects by means of a fundamental scale (Tab. I). The outcome of the pairwise comparison process are the preference matrices from which the normalised score of the alternatives and the local weight of criteria are computed. In the final step, scores and weights are linearly combined in order to obtain an overall score for each alternative. A ranking of the alternatives under analysis is obtained; according to AHP, the alternative which achieves the highest overall score is the best alternative of the analysed set.

Tab. I. Saaty's fundamental ratio scale

Verbal Judgement	Saaty's ratio scale $[w_j/w_k]$
very strong preference for object k	1/9
strong preference for object k	1/7
definite preference for object k	1/5
weak preference for object k	1/3
indifference	1
weak preference for object j	3
definite preference for object j	5
strong preference for object j	7
very strong preference for object j	9

According to authentic AHP, each pairwise comparison involves the DM which has to express verbal judgements in terms of the Saaty's fundamental verbal scale (Tab. I). In the scoring stage, the DM's verbal judgements are related to the performance of the alternatives on each criterion (i.e., the DM gives a verbal judgement on the alternatives based on the criterion satisfaction). Even if this process allows to manage qualitative indices, its main disadvantage is related to the intensive involvement of DM. With the aim to reduce subjectivity, the pairwise comparison process on a quantitative criterion can be addressed by computing the ratio of the performance index value of the alternatives. Moreover, this approach allows to automatize the pairwise comparison process. The automatized scoring stage exploited in the *MC-CBA toolkit* is based on this approach; furthermore, the obtained ratio values are converted to the Saaty's ratio scale by means of a scaling function. In the full report, the AHP model and the automatized pairwise comparison process are described in detail.

Case Study: MC-CBA toolkit for distribution grid planning

The case study concerns a distribution grid planning decision-making problem. In particular, the *MC-CBA toolkit* is used as decision support tool for identifying the best planning option among a set of feasible plans. Each plan is based on the Active Distribution Network approach (ADN) which combines traditional *network reinforcement solutions* with an active management of network assets (*non-network solutions*). In the case study, each plan involves traditional network reinforcements and the siting, sizing, and management of distributed energy storage (DES) as *non-network solution.* The decision-making problem is addressed from the utility perspective which propose the plans. In the case study scenario, the Distribution System Operator (DSO) owns the DESs and operates them for solving network contingencies; however, energy price arbitrage is not allowed. The economic assessment of the alternatives is based on the net present value (NPV). The NPV is evaluated by considering the monetary value of three different impacts:

- the investments for traditional network reinforcement solutions;
- the cost related to the reactive power exchange with the transmission grid;
- the investments for DES.

The criteria for evaluate the smart grid deployment merit are selected from the list proposed by JRC. Since this list is general purpose for smart grid context, the most suitable policy criteria (PCs) and the related key performance indicators (KPIs) are identified for the case study analysis:

1. *Policy Criterion* 1 (PC1)*:* Network connectivity and access to all categories of network users;
    A. KPI_{1A}: Operational flexibility provided for dynamic balancing of electricity in the network.
2. *Policy Criterion* 2 (PC2): Security and quality of supply;
    A. KPI_{2A}: Stability of the electricity system;
    B. KPI_{2B}: Duration of interruptions per customer;
    C. KPI_{2C}: Frequency of interruptions per customer;
    D. KPI_{2D}: Voltage quality performance – voltage variations.
3. *Policy Criterion 3* (PC3): Efficiency and service quality in electricity supply and grid operation;
    A. $KPI_{3A:}$ Level of losses in distribution networks.

The *MC-CBA toolkit* allows an automatized assessment of the planning alternatives under analysis. According to the DM's point of view, the alternative which achieves the highest overall score best satisfies the compromise among the technical and economic evaluation. With the aim to investigate the robustness of the result obtained, a sensitivity analysis is made by varying the relevance of the economic criterion with respect to the smart grid deployment merit criterion.

Closing Discussion

The *MC-CBA toolkit* is a decision support tool for decision-making problems on smart grid context. It automatizes the analysis of the planning options by rejecting the DM's subjectivity. The original automatic pairwise comparison procedure allows to address complex decision-making problems in which the number of the alternatives and/or of criteria is large. Since the *MC-CBA toolkit* does not require to convert all impacts in monetary terms, it provides a direct output-based assessment. The overall score of the alternative depends on the performances on the evaluation criteria and on the DM's perspective.

The beneficiaries of the *MC-CBA toolkit* are both system operators and regulatory bodies. The *MC-CBA toolkit* allows for a systematic and simultaneous assessment of different impacts. On one hand, system operators can evaluate the technical compliance of project options by considering mutually conflicting objectives. On the other hand, regulatory bodies can simultaneously assess monetary and non-monetary impacts while considering different stakeholder's perspectives. Since the MC-CBA analysis does not requires to convert all impacts in monetary terms, this combined approach is suitable for accounting the social aspects related to the power system planning.

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1 Introduction

Nowadays, due to the increasing presence of distributed energy resources and the integration of automation and communication technologies the electric power system is evolving towards the smart grid paradigm. In this scenario, to ensure a reliable, economic, sustainable, and safe energy supply, a smart integration of the actions of all grid users is required. Typically, smart grid projects are responsible of wide range impacts which span from the electrical power system to the entire society. Often, these impacts are not easily quantifiable thus an assessment based on their monetary value is not attainable. In this context, traditional approaches as the cost-benefit analysis (CBA) become unfit. A reliable assessment of several planning options can be obtained by using hybrid approaches which combine monetary appraisal tools within a generalised framework based on multi-criteria analysis (MCA). A combined MC-CBA approach does not require the monetisation of all impacts and it preserves the advantages of each methodology while overcoming the respective weaknesses.

This report describes the mathematical model of the MC-CBA methodology for smart grid project assessment proposed in previous activities for the Research Fund for the Italian Electrical System and ISGAN. The proposed MC-CBA approach is general purpose since it can be used for assessing different smart grid assets. This model is exploited by the original software *MC-CBA toolkit,* which is presented in this document. The *MC-CBA toolkit* allows for an output-based assessment of the alternatives based on an automated comparison procedure. The *MC-CBA toolkit* aims at supporting the decision makers (DMs) in identifying the best planning option by providing an assessment framework which rejects any personal bias. The proposed solution accords with the stakeholders' interests while complying with the economic constraints. Therefore, the aim of the proposed *MC-CBA toolkit* is to help DMs of companies and government bodies in strategic planning of smart grids. The *MC-CBA toolkit* decomposes the decision-making problem by dividing the impacts in three main areas: economic impacts, the contribution towards the smart grid realisation, the externality impacts. Since the systematic assessment considers simultaneously effects which belong to the different areas, companies are able to verify the performance achieved by the different options, while government bodies can consider both monetary and non-monetary impacts according to different views. Since the combined approach does not require to monetise all impacts, it is suitable for take into account the effects of power system planning on society and environment.

In order to illustrate the effectiveness of the *MC-CBA toolkit,* a case study focused on the project selection among different smart grid development plans is presented. More specifically, a set of different upgrading plans based on the Active Distribution Network (ADN) approach is analysed. The ADN approach differs from traditional *fit and forget* since it combines *network solutions* and active management strategies with the aim to maximise the exploitation of the existing infrastructure. The active management strategies are also known as *no-network solutions,* they involve e.g., reactive power management, system reconfiguration, generator dispatch, demand-side management. In the case study, along with line and substation upgrading, the siting, sizing, and management of Distributed Energy Storage (DES) devices is provided as a *no-network solution*. The Distribution System Operator (DSO) owns the DES devices which are used for network operation; conversely, their use for energy price arbitrage is forbidden.

In the case of *no-network* solutions, if optimally allocated, DESs can provide numerous technical and economic benefits such as voltage support, losses reductions, enhanced reliability and quality of service, improved hosting capacity, deferral of network investments, and operational expenditure (OPEX) reduction. Those benefits are not mutually exclusive because a single storage device can be used to offer different services [1]. In this scenario, a better understanding of the multiplicity of impacts a MC-CBA approach have to be exploited. The effectiveness of the planning process is improved, an approach focused on a single benefit or application cannot be effective to get the best planning alternative since the other capabilities could be disregarded. Furthermore, an output-based assessment which accounts the impacts in terms of their metrics rejects the distortion introduced by the monetary conversion techniques. As far as these characteristics, the case study involving the DES as *no-network* solutions has been identified as a case study for the *MC-CBA toolkit.* The presented tool implements an output-based evaluation framework which combines the economic assessment of monetary impacts and an objective performance assessment of no-monetary impacts.

The report is organised as follows, chapter 2 briefly resumes the achievements of the previous activities of Research on the Electrical System and describes the structure for decomposing the decision-making problem exploited by the *MC-CBA toolkit*. In chapter 3, the mathematical model used for solving the decision-making problem by means of the *MC-CBA toolkit* is described. This model relies on the Analytic Hierarchy Process (AHP) fundamentals; moreover, an automated procedure for pairwise compare the alternatives is exploited. Chapter **Errore. L'origine riferimento non è stata trovata.** presents the case study, a set of different upgrading plans based on the ADN approach is analysed for identifying the best planning option. Finally, chapter **Errore. L'origine riferimento non è stata trovata.** reports the closing discussion.

2 Model of the decision-making problem

2.1 The hierarchy of criteria

The proposed MC-CBA framework of the *MC-CBA toolkit* aims at evaluating different smart grid planning activities. The MC-CBA framework generalises the international guidelines on smart grid project assessment produced by the Joint Research Centre (JRC) [2], [3]. Moreover, the MC-CBA framework formalises the decision-making problems according to multi-criteria analysis.

The decision-making problem is decomposed in terms of a hierarchical tree of criteria formed by three independent branches to evaluate the impacts of the project options on three areas of interest. Figure 1 depicts the structure of the hierarchy of criteria. Each branch starts from a first level criterion 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. The three branches are independent therefore an impact can be evaluated through its effects on each area of interest. Conversely, on a same branch each impact has to be considered by means of a single effect in order to avoid double counting.

The *MC-CBA toolkit* appraises the project options by means of the described hierarchical structure of evaluation criteria. The *MC-CBA toolkit* is flexible, the number of the criteria for each branch can be chosen by the user.

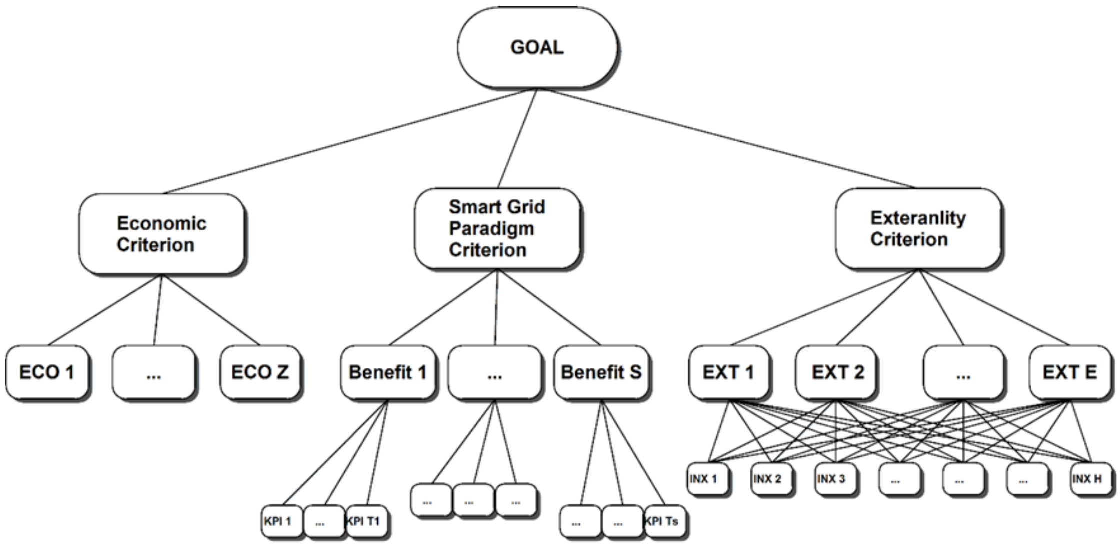

Figure 1. Hierarchical structure of criteria of the *MC-CBA toolkit*

2.2 The three evaluation branches

The head of the hierarchical tree is the goal of the decision-making problem; in this case it is the strategic objective of identifying the best smart grid planning option among the given set. This result is obtained by combining the results of the assessment on the three 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.

According to the related area of interest, the main goal of each branch is to identify the best planning option.

2.2.1 The economic evaluation branch

The economic criterion is the head node of the economic branch that aims at assessing the economic performance of the project options. This branch refers to the monetary impacts, the economic performances are measured by means of the output indexes provided by a CBA. The CBA of monetary impacts that can be done according to the procedure defined by JRC in [2], [4]. Figure 2 represents the economic branch which has three criteria in the second level, each terminal criterion appraises one of the CBA output indexes:

- the **Net Present Value (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. It is a quantitative criterion measured in terms of currency.
- The **Internal Rate of Return (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. It is a quantitative criterion measured in percentage terms.
- The **Cost-Benefit Ratio (CBR) criterion** measures the efficiency of the investment option. An alternative is positively evaluated if its CBR is greater than one. It is a quantitative dimensionless criterion.

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

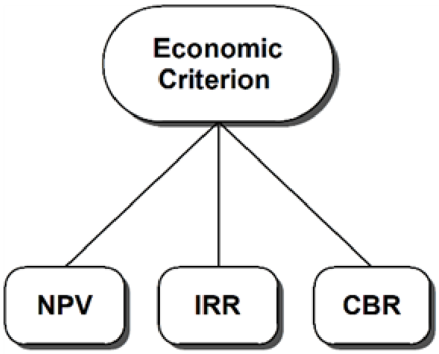

Figure 2. Economic tree based on the CBA output indices

Alternatively, the terminal criteria of the economic branch hierarchy are related to the project impacts in terms of the monetary costs and benefits. Figure 3 depicts a generalised economic branch with elementary costs and benefits explicitly accounted. In general, two sub-branches can be defined: the cost sub-branch and the benefit sub-branch.

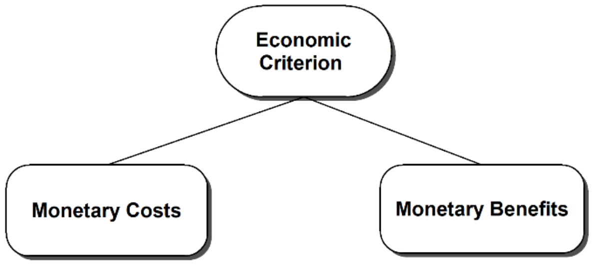

Figure 3. The economic branch with elementary cost and benefits

The performances on all criteria are measured in terms of currency, therefore criteria are fulfilled by performances that minimise costs and maximise monetary benefits. Therefore, the *MC-CBA toolkit* requires that the data related to costs have negative values, whereas the data related to monetary benefits have positive values.

2.2.2 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. The importance of this evaluation arises from the role of the smart grids in government policies. In [5] the European Commission (EC) defined a list of benefits for the energetic sector related to the smart grid development. Starting from the EC document, the Joint Research Centre (JRC) devised a list of *Policy Criteria* (PCs) with the aim to provide common assessment guidelines for smart grid projects [2]–[4]. Moreover, the fulfillment of the PCs is appraised by means of *Key Performance Indicators* (KPIs) [2]–[4]. The formulas useful for computing most of the KPIs have been also proposed by the JRC [3]. Generally, each evaluated KPI is referred to a baseline scenario. It is worth to highlight that the evaluation of the project options through KPIs is outcome oriented. In other words, by means of KPIs are not evaluated the technical features of the infrastructure but the produced effects.

The structure of the “smart grid paradigm branch” reflects the JRC approach; therefore, the second level criteria are the PCs 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, PCs are mutually independent. Furthermore, KPIs related to a same PC have the same relevance [2]–[4].

By default, the *MC-CBA toolkit* assumes that all KPIs are satisfied as the related impact metric increases, in order to be fulfilled the KPIs have to be maximises. Conversely, if some KPI is defined as it is satisfied by minimising the value of the related impact metric, the sign of the data related that metric has to be negative.

2.2.3 The externality impacts assessment

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 for 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, whereas a related 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 fulfilment 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.

By default, the *MC-CBA toolkit* assumes that all terminal criteria are satisfied as the related impact metric increases, in order to be fulfilled the terminal criteria have to be maximises. Conversely, if some terminal criterion is defined as it is satisfied by minimising the value of the related impact metric, the sign of the data related that metric has to be negative.

3 Analytic Hierarchy Process

3.1 Introduction

The *Analytic Hierarchy Process* (AHP) has been proposed by Thomas L. Saaty in the early 1970s. Regardless some theoretical criticism, the AHP is widely used for addressing decision-making problems on several sectors, it is one of the most acknowledged MCA methods [6]. The AHP is a Multi-Attribute Decision-Making (MADM) method which belongs to the full aggregation approach (FAA) family [7]. 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 objects. In general, the comparison depends on the personal judgments of the DM who has to provide information about the relative importance of one object over another. The results of the pairwise comparison process are the normalised scores for the alternatives and the local weights for the evaluation criteria. The overall score of each alternative is obtained by linearly combining the normalised scores obtained on each criterion and the criteria weights. The overall score represents the overall eligibility of each alternative; accordingly, the appraised alternatives are ranked; the best alternative of the analysed set is the one that achieves the highest overall score.

AHP helps the DM in organising the decision-making problem according to a hierarchy of criteria formed by the main objective, criteria, sub-criteria, and alternatives. Therefore, AHP forces the DM in decomposing the decision-making problem in elementary sub-problems which are systematically analysed one by one. Thus, the number of pairwise comparison to be addressed increases as the number of criteria and of alternatives increases.

3.2 The steps of the AHP

Generally, the AHP assessment requires 4 steps.

Step 1 – Decision-making problem formalisation

Firstly, the decision-making problem has to be formalised according to the MCA requirements: the evaluation criteria and their hierarchical structure, the alternatives under analysis and their performance metrics have to be defined. Therefore, a Performance Matrix[1] (PM) has to be built for collecting the performance indexes of the alternatives.

Step 2 – The pairwise comparison procedure

The pairwise comparison procedure is one of the key features of AHP since it is used both in the scoring and in the weighting stages. By means of the comparison between two object the preference assessment is elicited. In authentic AHP, the subjectivity of the decision maker influences both the scoring and weighting stage. The personal judgment of the decision maker is quantified on a standardized judgment scale (Saaty's scale), as shown in Table 1. 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. Even if scoring and weighting stages are two distinct phases of the AHP, the

[1] Matrix which collects for all the alternatives the values of the performance metrics considering all terminal criteria.

pairwise comparison procedure used to determine weights and scores is exactly the same. 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.

To illustrate, the local weights of criteria are obtained by means of the pairwise comparison procedure. For each sub-branch, the weights of the criteria belonging to the same level of the hierarchy are defined according to the DM preference. The DM judgements are collected by means of questions such as "In order to fulfil the parent criterion, how much the criterion A is relevant with respect to the criterion B?" [6]. The preferences of the stakeholders are 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 [8]

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. 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

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., $CR^{threshold} = 0{,}1$) [9]. Conversely, the consistency of large matrices is checked by means of statistical approaches [10].

Step 3 –Priority calculation

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 [8].

Step 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.

3.3 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;

3.4 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 [11].

3.5 Mathematical model of AHP

The key moment of the assessment based on AHP is the pairwise comparison procedure of criteria and alternatives. By means of this procedure, the criteria relevance and the performances of the alternatives are converted to common numerical scale.

In classical AHP, the subjectivity of the DM influences both the scoring and weighting stage. In the scoring stage, the normalised scores are obtained from the preferences expressed by the DM about the alternatives taking into account their performances contained in the PM. In the weighting stage, the criteria weights are obtained from the preferences of the stakeholders and reflect the criteria relevance. In this section the mathematical model behind these stages is described.

Definition: local and global weights of evaluation criteria

The criteria relevance depends on stakeholders' view, the criteria weights are defined accordingly. Each criterion has a local weight (or local priority) referred to the parent criterion and defined with respect to the other criteria which belong to the same level of the hierarchy. In fact, the local weight represents the relevance of one criterion over the others of the same level of the considered sub-branch with respect to the fulfilment of the parent criterion. Conversely, the global weight (or global priority) of each criterion measures its relevance with respect to the main goal at the head of the hierarchy. The global weight is computed from the local weights according to the hierarchical composition principle [8].

Once the global weights of all terminal criteria have been obtained, the overall score of the alternatives are computed by multiplying the matrix which of normalized scores of the alternatives with respect to the terminal criteria and the vector of global weights of the terminal criteria.

3.5.1 *The pairwise comparison procedure for weighting stage*

As already introduced, in AHP the weighting stage is based on the pairwise comparison procedure of criteria. This procedure allows to determine the local weight of each criterion with respect to the parent. According to the DM's view, the local weight is the numerical value which represent the relevance of a criterion on another for the fulfilment of the parent criterion.

The pairwise comparison procedure for determining the criteria weights regards two levels of the hierarchical structure. In a generic hierarchical structure, by considering:

- level $l=L-1$ the upper level, which hosts n criteria;
- level $l=L$ the lower level, which hosts m criteria (defined here as sub-criteria);

For each criterion which belongs to the level $L-1$ it is necessary to address a pairwise comparison procedure of the m sub-criteria. This process produces n preference matrixes which dimension is (m,m).

As already introduced, the pairwise comparison requires the DM's view which is collected by means of the Saaty's judgement verbal scale (Table 1). In the weighting stage, the question for collecting the DM's preference in the pairwise comparison procedure is structured as: "In order to fulfil the criterion $C_i^{(L-1)}$, how the criterion $C_j^{(L)}$ is important with respect to the criterion $C_{j+1}^{(L)}$?".

Where:

$C_j^{(L)}$, $C_{j+1}^{(L)}$ are the *j-th* and the *j+1-th* criteria of the level *L*;
$C_i^{(L-1)}$ is the parent criterion, the *i-th* criterion of the level *L-1*.

The preferences collected during the pairwise comparison procedure are converted in numerical values by using the equivalence defined by the Saaty's scale (Table 1). These numerical values are the entries of the preference matrix of the sub-criteria with respect to the parent criterion. Table 3 represents the preference matrix obtained from the pairwise comparison of the *m* sub-criteria of the level *L* with respect to the *i-th* parent criterion of the level *L-1*.

Table 3. Preference matrix of criteria

$\boldsymbol{C_i^{(L-1)}}$	$\boldsymbol{C_1^{(L)}}$	$\boldsymbol{C_2^{(L)}}$	**…**	$\boldsymbol{C_m^{(L)}}$
$\boldsymbol{C_1^{(L)}}$	1	$a_{1,2}^{(i)}$	…	$a_{1,m}^{(i)}$
$\boldsymbol{C_2^{(L)}}$	$\left(a_{1,2}^{(i)}\right)^{-1}$	1	…	$a_{2,m}^{(i)}$
…	…	…	1	…
$\boldsymbol{C_m^{(L)}}$	$\left(a_{1,m}^{(i)}\right)^{-1}$	$\left(a_{2,m}^{(i)}\right)^{-1}$	…	1

Where $a_{j,k}^{(i)}$ is the intensity of relevance of the *j-th* criterion over the *k-th* criterion, both of level *L,* with respect to the *i-th* parent criterion of level *L-1*. The numerical value of $a_{j,k}^{(i)}$ is in terms of the Saaty's rational scale.

The local weights (or local priorities) of the sub-criteria with respect to the parent criterion are obtained from the preference matrix by evaluating the normalised eigenvector related to the maximum eigenvalue. The generic entry of this eigenvector is $v_{j,i}^{(L)}$ which represents the local weight of the *j-th* sub-criteria of level *L* referred to the *i-th* parent criterion of level *L-1*. The vector $\overline{V_i^{(L)}}$ of the local weights of the *m* sub-criteria in level *L* referred to the *i-th* parent criterion of level *L-1* is represented by (1).

$$\overline{V_i^{(L)}} = \begin{bmatrix} v_{1,i}^{(L)} \\ \vdots \\ v_{m,i}^{(L)} \end{bmatrix} \quad (1)$$

Once the pairwise comparison of the *m* sub-criteria has been accomplished for all the *n* parent criteria of level *L-1*, it is possible to build the matrix of local weights $\underline{V^{(L)}}$ of criteria of the level *L* with respect to the criteria of level *L-1* (2).

$$\underline{V^{(L)}} = \left[\overline{V_1^{(L)}}, \dots, \overline{V_n^{(L)}}\right] = \begin{bmatrix} v_{1,1}^{(L)} & \cdots & v_{1,n}^{(L)} \\ \vdots & \ddots & \vdots \\ v_{m,1}^{(L)} & \cdots & v_{m,n}^{(L)} \end{bmatrix} \quad (2)$$

3.5.2 *The pairwise comparison procedure for scoring stage*

In MCA methods, the scoring stage allows for converting all performance indexes towards a common normalised scale. In AHP the scoring stage relies on the pairwise comparison procedure of the alternatives. In this procedure, the DM has to express his preferences on the alternatives with respect to each terminal criterion of the hierarchy. The preferences are collected by means of the Saaty's judgement verbal scale (Table 1). For each terminal criterion a preference matrix of alternatives is obtained.

In a generic hierarchical structure, by considering *h* terminal criteria and a set of *R* alternatives, the scoring stage produces *h* preference matrixes which dimension is (*R*,*R*). The generic preference matrix of the alternatives with respect to the *i-th* terminal criterion is represented in Table 4

Table 4. Preference matrix of the alternatives

Criterion i-th	Alternative 1	Alternative 2	…	Alternative R
Alternative 1	1	$q_{1,2}^{(i)}$	…	$q_{1,R}^{(i)}$
Alternative 2	$\left(q_{1,2}^{(i)}\right)^{-1}$	1	…	$q_{2,R}^{(i)}$
…	…	…	1	…
Alternative R	$\left(q_{1,R}^{(i)}\right)^{-1}$	$\left(q_{2,R}^{(i)}\right)^{-1}$	…	1

By considering the *i-the* terminal criterion, the entry $q_{j,k}^{(i)}$ represents the ratio between the level of fulfilment achieved by the alternative *j-th* and the level of fulfilment achieved by the alternative *k-th.*

The entries of the preference matrix can be obtained according to two different approaches:

- as in the classical AHP, from the DM's view by means of the Saaty's judgement scale;
- by calculating the ratio of the performance indexes reported in the PM.

The first approach involves the DM's view; therefore, subjectivity is introduced in the scoring stage. Conversely, the second approach the elements $q_{j,k}^{(i)}$ are obtained by means of a mathematical procedure that can be automated.

By considering two generic alternatives A_j and A_k, their pairwise comparison procedure with respect to the *i-th* terminal criterion involves their performance indexes: $d_j^{(i)}$ for alternative *j-th* and $d_k^{(i)}$ for the alternative *k-th*. In order to collect the verbal judgement from the DM, the question can be structured as: "On the basis of the respective performances $d_j^{(i)}$ and $d_k^{(i)}$, how the alternative A_j is preferred to the alternative A_k in order to fulfil the *i-th* criterion?". The answer of the DM has to be collected according to the Saaty's judgement scale, the numerical value $q_{j,k}^{(i)}$ is defind by means of the correspondence defined by the judgement scale.

Otherwise, if the preference matrices are obtained according to the mathematical approach, their entries are evaluated as in (3).

$$q_{j,k}^{(i)} = \frac{d_j^{(i)}}{d_k^{(i)}} \tag{3}$$

Where:

$q_{j,k}^{(i)}$ represents the preference on the alternative *j-th* over the alternative *k-th* with respect to the criterion *i-th*.

$d_j^{(i)}$ is the value of the performance indicator of the alternative *j-th* with respect to the *i-th* criterion;

$d_k^{(i)}$ is the value of the performance indicator of the alternative *k-th* with respect to the *i-th* criterion;

According to AHP postulates, the value of the entries $q_{j,k}^{(i)}$ has to be bounded [9].

The preference matrix related to the *i-th* terminal criterion is obtained once when the pairwise comparison of the *R* alternatives have been completed.

Regardless the approach which has been exploited for evaluating the entries of the preference matrix, the normalised score $s_{r,i}$ of the *r-th* altermative with respect to the *i-th* terminal criterion is the *r-th* element of the normalized eigenvector of the maximum eigenvalue of the preference matrix. The normalized scores of the *R* alternatives with respect to the *i-th* criterion are represented by the vector $\overline{S_i}$ (4).

$$\overline{S_i} = \begin{bmatrix} s_{1,i} \\ \vdots \\ s_{R,i} \end{bmatrix} \tag{4}$$

For calculating all normalised scores, the described procedure has to be repeated for all *h* terminal criterion of the hierarchy. As a result, *h* preference matrices of alternative which dimension is (*R,R*) are obtained. Each matrix provides a vector of normalised scores, by aggregating those vectors is possible to obtain the matrix $\underline{S}$ of normalised scores of the *R* alternatives (5).

$$\underline{S} = \left[\overline{S_1}, \overline{S_2}, \dots, \overline{S_h}\,\right] = \begin{bmatrix} s_{1,1} & \cdots & s_{1,h} \\ \vdots & \ddots & \vdots \\ s_{R,1} & \cdots & s_{R,h} \end{bmatrix} \tag{5}$$

3.5.3 The hierarchical composition principle

Evaluation of global weights

Each evaluation criterion has its relevance with respect to the main goal of the hierarchical structure which it belongs. The global weight (or global priority) is the numerical value that measures this global relevance. Conversely, the local weight (or local priority) is the numerical value which represents the relevance of a criterion with respect to the other criteria that belong to the same level of the sub-branch. The global weight of terminal criteria is fundamental for evaluate the overall scores of the alternatives.

The evaluation of global weights is a *top-bottom* procedure, by considering a hierarchical structure formed by *L* levels, such that *l*=1, 2, …, *L*. Each level *l* holds a finite number of criteria.

In the first level, the global weight of the criteria is equal to their local weight since the main goal of the hierarchy is the only criteria in the upper level.

The local weights of the first level criteria are represented by means of the vector $\bar{V}^{(1)}$ which dimension is (*n*, 1), as in (6).

$$\overline{V^{(1)}} = \begin{bmatrix} v_1^{(1)} \\ \vdots \\ v_n^{(1)} \end{bmatrix} \tag{6}$$

Where:

n is the number of criteria in the level *l*=1;

$v_i^{(1)}$ is the global weight of the *i-th* criterion of the level *l*=1.

Assuming that the level *l*=2 of the hierarchical structure hosts *m* criteria, each of them is characterised by *n* local weights. Therefore, for each criteria of the level *l*=2 exists a row vector $\bar{V}_i^{(2)}$ which entries are the local weights of the *i-th* criterion, as in (7).

$$\overline{V_i^{(2)}} = [v_{i,1}^{(2)}, v_{i,2}^{(2)}, \dots, v_{i,n}^{(2)}] \tag{7}$$

Where:

$\overline{V_i^{(2)}}$ is row vector of local weights of the *i-th* criterion of level *l*=2, which dimension is (1,*n*);

$v_{i,j}^{(2)}$ is local weight of the *i-th* criterion of the level *l*=2 referred to the parent criterion *j-th* of level *l*=1.

Since *m* are the criteria in level *l*=2, *m* row vectors as in (7) exist. The matrix of the local weights of the criteria in level *l*=2 is obtained by aggregating the row vectors as in (8).

$$\underline{V^{(2)}} = \begin{bmatrix} v_{1,1}^{(2)} & \cdots & v_{1,n}^{(2)} \\ \vdots & \ddots & \vdots \\ v_{m,1}^{(2)} & \cdots & v_{m,n}^{(2)} \end{bmatrix} \tag{8}$$

Where:

$\underline{V^{(2)}}$ is the matrix of local weights in the level *l*=2, which dimension is (*m,n*).

The global weights of the criteria in level *l*=2 are evaluated by multiplying $\underline{V^{(2)}}$, the matrix of the local weights of the criteria in level *l*=2, and $\overline{V^{(1)}}$, the vector of global weights of the criteria in level *l*=1, as in (9).

$$\overline{W^{(2)}} = \underline{V^{(2)}} \cdot \overline{V^{(1)}} = \begin{bmatrix} w_1^{(2)} \\ \vdots \\ w_m^{(2)} \end{bmatrix} \tag{9}$$

Where:

$\overline{W^{(2)}}$ is the vector of global weights of criteria in level *l*=2, which dimension is (*m,1*);

$w_i^{(2)}$ is the global weight of the *i-th* criterion of level *l*=2.

Assuming that the level *l*=3 of the hierarchy hosts *p* criteria, each of them is characterised by *m* local weights, since *m* are the parent criterion in level *l*=2. For each criterion of level *l*=3 a vector of local weights as in (10) exists.

$$\overline{V_i^{(3)}} = [v_{i,1}^{(3)}, v_{i,2}^{(3)}, \dots, v_{i,m}^{(3)}] \tag{10}$$

Where:

$\overline{V_i^{(3)}}$ is the row vector of local weights of the *i-th* criterion of level *l*=3, which dimension is (*1, m*);

$v_{i,j}^{(3)}$ is the local weight of the *i-th* criterion of the level *l*=3 with respect to the *j-th* parent criterion of level *l*=2.

The matrix $\underline{V^{(3)}}$ of the local weights of the criteria in the level *l*=3 is obtained by composing the *p* row vectors as in (11).

$$\underline{V^{(3)}} = \begin{bmatrix} v_{1,1}^{(3)} & \cdots & v_{1,m}^{(3)} \\ \vdots & \ddots & \vdots \\ v_{p,1}^{(3)} & \cdots & v_{p,m}^{(3)} \end{bmatrix} \tag{11}$$

Where:

$\underline{V^{(3)}}$ is matrix of the local weights of the criteria in the level l=3, which dimension is (p, m).

The global weights of the criteria in level l=3 are obtained by multiplying the matrix $\underline{V^{(3)}}$ and the vector $\overline{W^{(2)}}$, as in (12).

$$\overline{W^{(3)}} = \underline{V^{(3)}} \cdot \overline{W^{(2)}} = \underline{V^{(3)}} \cdot \underline{V^{(2)}} \cdot \overline{V^{(1)}} = \begin{bmatrix} w_1^{(3)} \\ \vdots \\ w_p^{(3)} \end{bmatrix} \tag{12}$$

Where:

$\overline{W^{(3)}}$: is the vector of global weights of the criteria in level l=3, which dimension is (p,1);
$w_i^{(3)}$: global weight of the *i-th* criterion of level l=3.

As one can see in (12), the vector of global weights of the criteria in level l=3 is obtained as the product of the matrix of local weight of the level l=3 and the matrixes of the local weight of upper levels. Generalising the procedure, if the hierarchical structure of criteria has L levels and h terminal criteria, the global weights of the terminal criteria are evaluated as in (13).

$$\overline{W^{(L)}} = \prod_{i=1}^{L} \underline{V^{(i)}} \tag{13}$$

Where:

$\overline{W^{(L)}}$: vector of global weights of the criteria in level l=L, which dimension is (h, 1);
$\underline{V^{(i)}}$: matrix of local weights of the criteria of the *i-th* level of the hierarchy.

Similarly, the global weights of the intermediate *j-th* level of the hierarchical structure are obtained as the product of the matrix of local weights of the criteria in level *j-th* and the matrixes of the local weight of the criteria in the levels above.

Evaluation of the overall score of the alternatives

Once the vector $W^{(L)}$ of the global weights of the h terminal criteria and the matrix $\underline{S}$ of normalised scores of the R alternatives are obtained, the overall score of each alternative is obtained as in (14).

$$\overline{P} = \underline{S} \cdot \overline{W^{(L)}} = \begin{bmatrix} s_{1,1} & \cdots & s_{1,h} \\ \vdots & \ddots & \vdots \\ s_{R,1} & \cdots & s_{R,h} \end{bmatrix} \cdot \begin{bmatrix} w_1^{(L)} \\ \vdots \\ w_h^{(L)} \end{bmatrix} = \begin{bmatrix} p_1 \\ \vdots \\ p_R \end{bmatrix} \tag{14}$$

Where:

$\overline{P}$ is the vector of the overall score of the alternatives, its dimension is $(R, 1)$;

$\underline{S}$ is the matrix of normalised scores of the alternatives with respect to each terminal criterion, its dimension is (R,h);

$s_{i,j}$ is the normalised score of the *i-th* alternative with respect to the *j-th* criterion;

$w_k^{(L)}$ is the global weight of the *k-th* terminal criterion;

p_i is the overall score of the *i-th* alternative.

3.5.4 Scoring stage in AHP

Qualitative pairwise comparison (authentic AHP)

Basically, in the scoring stage the data contained in the PM are converted in normalised scores by using the preference matrices obtained in the pairwise comparison procedure. As illustrated, in classical AHP the numerical values of the entries of the preference matrices are based on a subjective assessment of the performance in PM made by the DM. The main advantage of this approach is that the verbal judgments allows for a qualitative appraisal of intangible impacts. Conversely, the main disadvantage is related to the subjectivity introduced in the assessment even if quantitative data is available.

Quantitative pairwise comparison

An alternative approach to the qualitative pairwise comparison is to evaluate the entries of the preference matrices as the ratio of the quantitative performance indicators. According to AHP postulates, the values obtained have to be bounded [9]. The main advantage of this approach is the objectivity of the assessment; furthermore, since the DM is not directly involved, the whole procedure can be automated. However, the obtained values are not in terms of the Saaty's ratio scale.

Scaling of the quantitative pairwise comparison

With the aim to automate the pairwise comparison process by preserving the use of the Saaty's ratio scale, the values obtained as the ratio of quantitative indexes are converted by means of a scaling function. The automated scoring procedure exploited by the *MC-CBA toolkit* generalises the methodology proposed in [12]. The scaling function S converts the ratio value in terms of the Saaty's ratio scale (**Errore. L'origine riferimento non è stata trovata.**). The algorithm used by the *MC-CBA toolkit* for the automated pairwise comparison is represented in Figure 4 [13].

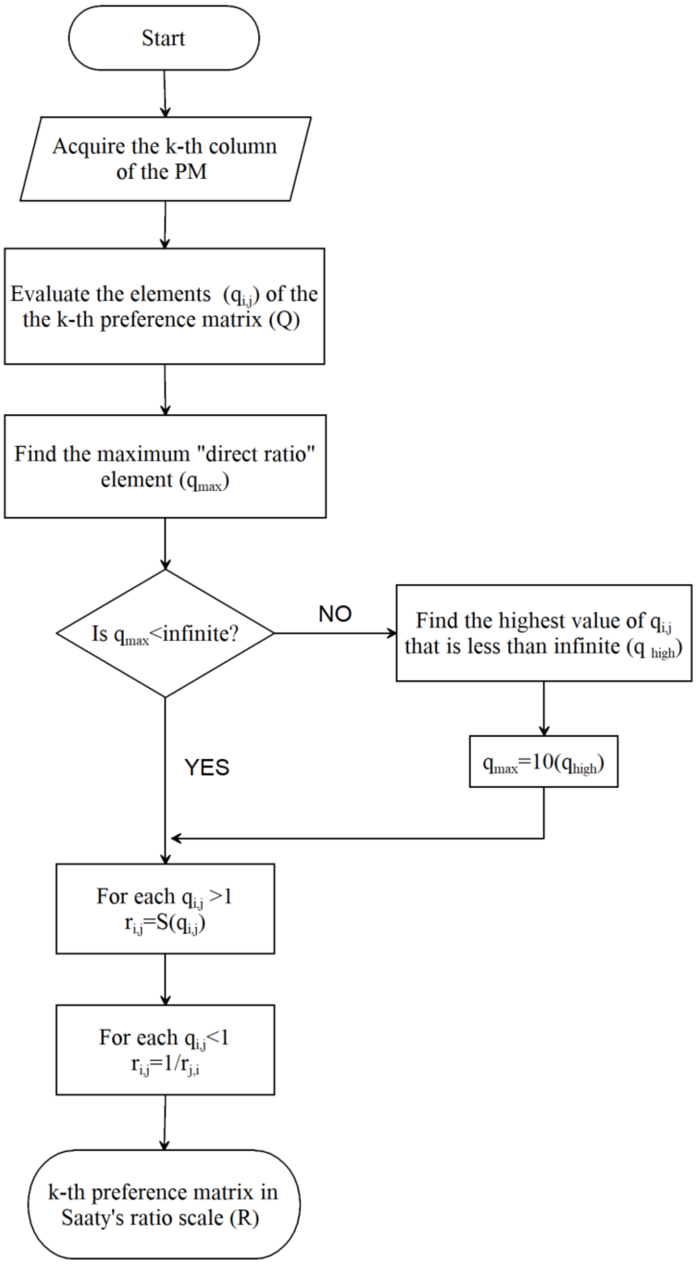

Figure 4. Flux diagram of the automated pairwise comparison procedure of the MC-CBA toolkit [13]

Firstly, for each *k-th* criterion is evaluated a “direct ratio” preference matrix $Q^{(k)}$ whose entries are $q_{i,j}^{(k)} = a_i^{(k)}/a_j^{(k)}$, where $a_i^{(k)}$ and $a_j^{(k)}$ are, respectively, the performances of the *i-th* and the *j-th* alternative on the *k-th* criterion. According to the straightforward use of the Saaty’s ratio scale, the value of $q_{i,j}^{(k)}$ expresses how much the *i-th* alternative is preferred than the *j-th* one. With the aim to exploit the AHP methodology for the analysis, the obtained $q_{i,j}^{(k)}$ values have to be converted in terms of the Saaty’s scale. Therefore, the scaling function S in (15) is employed.

$$r_{i,j}^{(k)} = S\left(q_{i,j}^{(k)}\right) = round\left(1 + \frac{(R_{max} - R_{min}) \cdot \left(q_{i,j}^{(k)} - 1\right)}{q_{max}^{(k)} - 1}\right) \tag{15}$$

Where

$r_{i,j}^{(k)}$ is the image of the element $q_{i,j}^{(k)}$ in the new scale;

$q_{max}^{(k)}$ is the maximum value among all the $q_{i,j}^{(k)}$;

R_{max} and R_{min} are the maximum and the minimum value of the preferences in the destination scale; if the destination scale is the Saaty's ratio scale: $R_{max} = 9$ and $R_{min} = 1$.

The preferences in terms of the Saaty's ratio scale are integer values, therefore the values obtained from the scaling function are rounded.

If all performance values of the alternatives are different from zero, the value of $q_{max}^{(k)}$ is finite thus the scaling function S can be applied. Conversely, if at least one alternative has a performance equal to zero, the value of $q_{i,j}^{(k)}$ is a division by zero. In this case, if $q_{i,j}^{(k)}$ is evaluated as a mathematical limit, the value of $q_{max}^{(k)}$ tends to infinity. In addition to the model in [12], to avoid this event without losing the generality of the scaling process, the proposed automatic pairwise comparison algorithm finds $q_{high}^{(k)}$ which is the highest $q_{i,j}^{(k)}$ less than infinite. Once the $q_{max}^{(k)}$ value is obtained, the scaling function S is applied to the modified "direct ratio" preference matrix $Q^{(k)}$. The scaling function S is applied on all the entries of $Q^{(k)}$ greater than 1; the related elements on the other side of the diagonal of the matrix are obtained by evaluating the reciprocal value. Finally, the preference matrix $R^{(k)}$ related to the *k-th* criterion is obtained, it represents the imagine of the matrix $Q^{(k)}$ in terms of the Saaty's scale.

The described automated pairwise comparison procedure is exploited for each column of the PM. If the sign of elements of the considered column of the PM differs, the values have to be shifted to obtain a column of elements with the same sign and exploit the automated pairwise comparison procedure described. The quantity which is added to all the elements of the column is equal to the difference between the highest and the lower value.

The automated pairwise comparison procedure assumes that all terminal criteria of the hierarchy are satisfied by increasing values of performance indicators. In order to consider terminal criteria which have to be minimised, the related column of the PM has to be changed in sign.

4 Case study

The case study proposed for presenting the *MC-CBA toolkit* is focused on the project selection of a reinforcement plan of a Medium Voltage (MV) distribution network. The planning alternatives under analysis are a set of plans based on the ADN approach. Along with line and substation upgrading, the siting, sizing, and management of Distributed Energy Storage (DES) devices is provided as a *no-network solution*. The point of view of the DSO is adopted for the planning process. The DSO owns the DES devices which are used for network operation; conversely, their use for energy price arbitrage is forbidden.

4.1 The distribution network under analysis

The decision-making process involves a portion of the distribution grid which represents the typical rural scenario; the network is weakly meshed with emergency tie connections and radially operated. As represented in Figure 5, the network is fed by two primary substations (nodes 1 and 2) and it has 22 MV nodes. The radial structure is divided into four zones: A1, B1, B2, C1. The zone A1 is an urban area characterised by two underground feeders. The zones B1 and B2 are rural areas fed by means of overhead feeders and several distributed generators. The zone C1 is a passive rural area fed by a lateral branch. The underground feeders are 95 mm^2 MV cables, while overhead MV lines trunk feeders and lateral branches have sections of 35 mm^2 and 16 mm^2 respectively.

4.2 The planning alternatives under analysis

The novel ADN approach differs from traditional *fit and forget* since it combines *network solutions* and active management strategies with the aim to maximise the exploitation of the existing infrastructure. The active management strategies are also known as *no-network solutions,* they involve e.g., reactive power management, system reconfiguration, generator

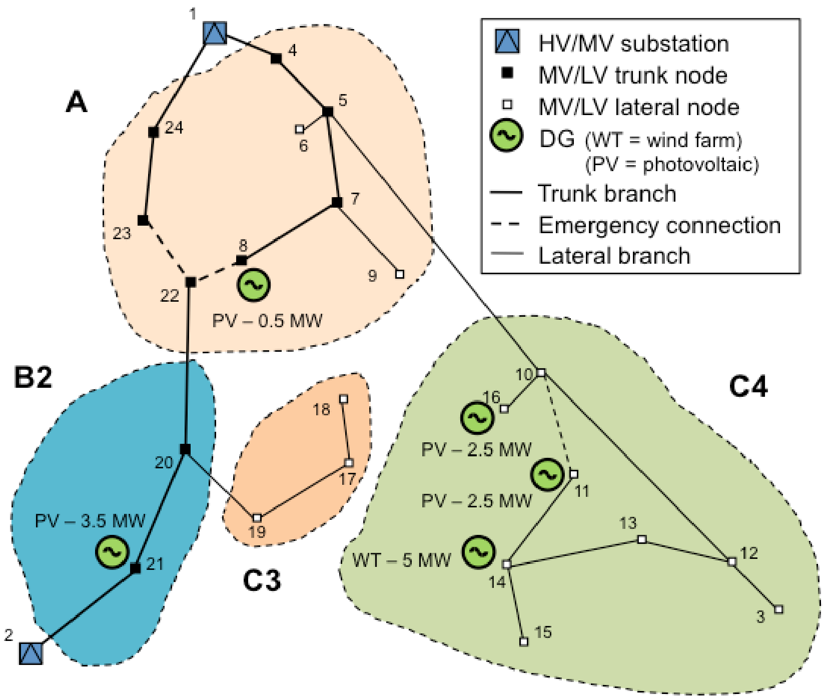

Figure 5. Distribution network of the case study [14]

dispatch, demand-side management. In this case study, along with line and substation upgrading, the siting, sizing, and management of Distributed Energy Storage (DES) devices is provided as a *no-network solution*. The aim of this report is to present a systematic framework for project analysis and selection, the information required by the presented MC-CBA framework is only related to the performance achieved by each planning option, at this stage the assessment does not require information about how a reinforcement plan has been devised. However, for the sake of completeness, a brief description of the process which devised the alternatives is given. Each reinforcement plan under analysis has been devised by a multi-objective planning optimisation. A Pareto front has been obtained by using the procedure described in [14]. Each plan has a time horizon of 10 years, the network topology and the number of distributed generators are fixed. A load growth rate of 3% per year is considered for each MV/LV node. Uncertainties have been introduced by modelling loads and generators with typical daily profiles and normal probabilistic distribution functions. The technical constraint violation risk is evaluated hourly by means of a probabilistic load flow. The generation curtailment has not been exploited for DG. Steady state and emergency configurations are assessed. The multi-objective optimisation planning procedure considered 9 objectives: network investment, energy losses, reactive power exchange with the Transmission System Operator (TSO), quality of service in terms of number of interruptions, quality of service in terms duration of the interruptions, quality of service in terms of voltage dips, voltage profile quality, black start support, and DES investment. The DES devices considered are Li-ion batteries with 10 years of expected lifetime. Each reinforcement plan is characterised by up to 2 DES devices having a nominal power within the range 100 kW ÷ 3 MW and a nominal duration within the range 1 ÷ 10 hours. The Distribution System Operator (DSO) owns the DES devices which are used for network operation; conversely, their use for energy price arbitrage is forbidden.

4.3 Selection of the evaluation criteria

Since the *MC-CBA toolkit* is general purpose for smart grid assets, it is required a preliminary stage for identifying the relevant criteria for the particular decision-making problem at hand [6]. In order to obtain an effective assessment, it is necessary to identify the relevant criteria which highlight the differences among the alternatives. The hierarchy of evaluation criteria selected for the assessment in the present case study is depicted in Figure 6.

Since the set of the alternative under analysis contains the reference scenario, for the sake of clarity is defined:

- *Business as Usual* (BaU) scenario: reference scenario in which no smart grid solution are developed [3]. In the case study, no DES devices are installed in the distribution network in the BaU scenario. Thus, the load growth is faced only by traditional network reinforcement solutions.
- S*mart grid* (SG) scenario: scenarios in which also smart grid solutions are developed [3]. In the case study, the SG scenario concerns the DES devices as no-network solutions, each option belonging to the SG scenario is characterised by a different site, size, and location of the device.

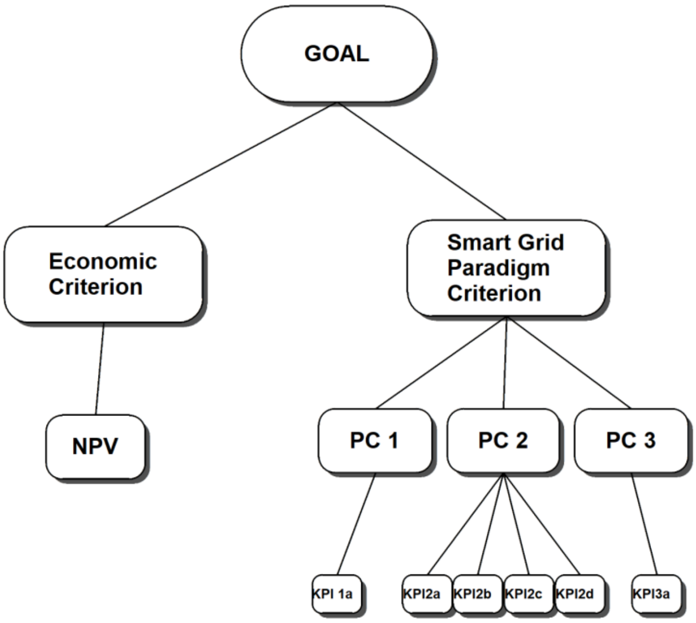

Figure 6. Overview of the hierarchy of evaluation criteria

4.3.1 The economic branch

In general, the *MC-CBA toolkit* evaluates the economic performance achieved by the alternatives on a CBA. In the case study, the economic assessment is based on the performance achieved by the alternatives in terms of Net Present Value (NPV). This indicator is evaluated by means of a CBA which concerns the three monetary impacts:

- the investment cost of traditional network reinforcement solutions;
- the investment cost in DES devices;
- the cost related to the reactive power exchange with the transmission grid.

As depicted in Figure 6, the economic branch is formed by a single terminal criterion. The alternative which achieves the highest NPV is the best option according to the economic evaluation.

4.3.2 Smart grid deployment merit branch

The smart grid deployment merit is evaluated by means of the list of criteria proposed by the JRC [2], [3]. The proposed list is general purpose for the smart grid context, therefore the most suitable subset of criteria has to be identified according to the decision-making problem at hand. The 3 Policy Criteria (PCs) and the related Key Performance Indicators (KPIs considered in the present case study are:

1) *Policy Criterion* 1 *(PC1):* Network connectivity and access to all categories of network users;
   a) KPI_{1A}: Operational flexibility provided for dynamic balancing of electricity in the network.

2) *Policy Criterion* 2 (PC2): Security and quality of supply;
    a) KPI_{2A}: Stability of the electricity system;
    b) KPI_{2B}: Duration of interruptions per customer;
    c) KPI_{2C}: Frequency of interruptions per customer;
    d) KPI_{2D}: Voltage quality performance – voltage variations.
3) *Policy Criterion 3* (PC3): Efficiency and service quality in electricity supply and grid operation;
    a) KPI_{3A}: Level of losses in distribution networks.

PC1 - Network connectivity and access to all categories of network users

KPI_{1A} - Operational flexibility provided for dynamic balancing of electricity in the network

The KPI_{1A} evaluates the contribution in terms of flexibility given by the alternative to the operation of the grid. This contribution depends on the dispatchable resources available in the network. In the case study, DES devices are the only dispatchable units. Considering the available information on the expansion plans, the KPI_{1A} is evaluated by (16).

$$\mathrm{KPI_{1A}} = \sum_{i=1}^{N_{DES}} \frac{(\hat{P}_{DES,i}^{(out)})_{SG} + \left|(\hat{P}_{DES,i}^{(in)})_{SG}\right|}{2} \qquad [MW] \tag{16}$$

Where:

N_{DES} is the number of DES devices provided by the alternative;

$(\hat{P}_{DES,i}^{(out)})_{SG}$ is the expected maximum power generated by the *i-th* device in the planning horizon;

$(\hat{P}_{DES,i}^{(in)})_{SG}$ is the expected maximum power adsorbed from the grid by the *i-th* device in the planning horizon.

The alternative which contributes more to operational flexibility is the one which achieves the maximum value of the $\mathrm{KPI_{1A}}$.

PC2 - Security and quality of supply

KPI_{2A} - Stability of the electricity system

The KPI_{2A} evaluates the contribution of the planning alternatives in relieving the possible sources of system instability. JRC suggests simulating the system behaviour in several extreme scenarios [3]. Since the available information on the alternatives, a different approach is used. Taking into account that DES devices can contribute to network black-start, a potential ex-post contribution to the system reliability is considered in this case study. The performance indicator for KPI_{2A} is computed by (17).

$$\mathrm{KPI}_{2\mathrm{A}} = P_{BS} = \sum_{i=1}^{N_{DES}} \sum_{h=1}^{N_h} \min(SoC_{h,i} \cdot \eta_{dis,i}, P_{n,i}) \quad [MW] \tag{17}$$

Where:

P_{BS} is the amount of active power available for the black-start service;

N_h is the number of time intervals of the planning period;

N_{DES} is the number of DES devices provided by the alternative;

$SoC_{h,i}$ is the state of charge of the *i-th* device in the *h-th* time interval;

$\eta_{dis,i}$ is the discharging efficiency of the *i-th* device;

$P_{n,i}$ is the nominal power of the *i-th* device.

The planning option that achieves the highest value of $\mathrm{KPI}_{2\mathrm{A}}$ better performs in terms of black-start support.

KPI₂B - Duration of interruptions per customer

The $\mathrm{KPI}_{2\mathrm{B}}$ evaluates the contribution of the planning alternatives in reducing the duration of the interruptions for each customer; therefore, the $\mathrm{KPI}_{2\mathrm{B}}$ corresponds to the System Average Interruption Duration Index (SAIDI), it is evaluated as shown in (18).

$$KPI_{2B} = SAIDI = \frac{\sum_{i=1}^{n} U_i NC_i}{\sum_{i=1}^{n} NC_i} \quad \left[\frac{occ.}{yr}\right] \tag{18}$$

Where:

U_i is the duration of outages for the customers in the *i-th* bus;

NC_i is the number of customers in the *i-th* bus;

n is the number of busses in the network.

The planning option that achieves the lowest value of $\mathrm{KPI}_{2\mathrm{B}}$ better performs in terms of duration of interruptions.

KPI_{2C} - Frequency of interruptions per customer

The $\mathrm{KPI}_{2\mathrm{C}}$ evaluates the contribution of the planning alternatives in reducing the frequency of interruptions for each customer; therefore, the $\mathrm{KPI}_{2\mathrm{C}}$ corresponds to the System Average Interruption Frequency Index (SAIFI), it is evaluated as shown in (19).

$$KPI_{2C} = SAIFI = \frac{\sum_{i=1}^{n} \lambda_i NC_i}{\sum_{i=1}^{n} NC_i} \quad \left[\frac{hr}{yr}\right] \tag{19}$$

Where:

λ_i is the failure rate in the *i-th* bus;

NC_i is the number of customers in the *i-th* bus;

n is the number of busses in the network.

KPI_{2D} - Voltage quality performance – voltage variations

The KPI_{2D} evaluates the contribution of the planning alternatives in rejecting voltage variations. DES can contribute to voltage regulation by means of the power factor management. In this paper, the KPI_{2D} is evaluated by (20).

$$KPI_{2D} = \sum_{i=1}^{n} \sum_{h=1}^{N_h} \left| V_{max.i}^{(h)} - V_{min.i}^{(h)} \right| \tag{20}$$

Where:

n is the number of busses in the network;

N_h is the number of time intervals of the planning period;

$V_{max.i}^{(h)}$ is the maximum voltage value in the *i-th* bus at the *h-th* interval;

$V_{min.i}^{(h)}$ is the minimum voltage value in the *i-th* bus at the *h-th* interval;

The planning option that achieves the lowest value of KPI_{2D} better performs in terms of voltage variations.

PC3 - Efficiency and service quality in electricity supply and grid operation

KPI_{3A} - Level of losses in distribution networks

The KPI_{3A} evaluates the contribution of the planning alternatives in reducing the network energy losses. DES can contribute in reducing network losses by providing the peak shaving service. The KPI_{3A} is evaluated by (21).

$$KPI_{3A} = \sum_{j=1}^{N_e} \sum_{k=1}^{N_h} E_{L_{j,k}} \quad [MWh] \tag{21}$$

Where:

N_h is the number of time intervals of the planning period;

N_e is the number of element considered for the assessment of energy losses (HV/MV transformers, lines);

$E_{L_{j,k}}$ is the energy loss of the *j-th* element in the *k-th* time interval.

The planning option that achieves the lowest value of KPI_{3A} better performs in terms of energy losses.

4.3.3 Externality branch

The decision-making problem is addressed from the utility perspective which proposes the plans, the externality impacts have been neglected due to the unavailability of data.

4.4 Performance Matrix of the alternatives

The planning options considered in the case study involve siting of a DES device in one of the 22 buses of the MV network along with reinforcement solutions. An overview of DES siting and sizing of the alternatives is given in Table 5. The MC-CBA framework is output-based, only the data required by the assessment is reported, the PM of the alternative is shown in Table 6. The alternative labeled A_1 is the baseline scenario, hence no DES devices are involved in. The values in Table 6 are obtained from data provided as output by the multi-objective planning optimization process which devised the alternatives. Therefore, the values are based on simulating the scenario related to each alternative for the whole planning period.

Table 5. Topological information on DES

Alternative	Bus	P_{SdA} [kW]	E_{SdA} [kWh]
A_1	No DES	0	0
A_2	7	100	100
A_3	14	200	400
A_4	16	100	100
A_5	14	100	100

Table 6. PM of the decision-making problem

Alternative	PM_ECO	PM_SG					
	NPV [k€]	KPI_{1A} [MW]	KPI_{2A} [MW]	KPI_{2B} $\left[\frac{occ.}{yr}\right]$	KPI_{2C} $\left[\frac{hr}{yr}\right]$	KPI_{2D} [p.u.]	KPI_{3A} [MWh]
A_1	0	0	0	2.026	0.837	11.48	11216.1
A_2	4.257	66.2	1269.2	2.017	0.751	10.68	10677.7
A_3	3.371	184.2	2903.9	2.017	0.751	10.68	10701.3
A_4	12.905	48.4	984.6	2.017	0.751	10.68	10661.3
A_5	88.587	38.2	574.1	2.017	0.751	10.69	10682.4

4.5 Local and global weights of criteria

MCA requires to define a numerical weight for each criterion according to their relevance for the DM or stakeholders. The economic branch has in its lower level a unique criterion, the local weight of the NPV criterion is equal to 1.

The smart grid deployment merit branch is divided into 3 sub-branches. According to JRC recommendation [2], [3], criteria belonging to the same level of the hierarchy have the same weight; therefore, the PCs have the same relevance: their local weight is 1/3. Furthermore, the local weight of KPI_{1A} and KPI_{3A} is 1, whereas the local weight of each KPI related to PC2 is equal to 0.25. By considering an equal relevance of the two branches (in Table 7 the local weights of the first level criteria is reported) the hierarchical tree has been evaluated according to the hierarchical composition principle; the resulting global weights of the terminal criteria are shown in Table 8.

Table 7. Local weight of the first level criteria

Branch	Local weight
Economic	0.5
Smart grid merit	0.5
Externality	0

Table 8. Global weights of terminal criteria

Terminal criterion	Global weight
NPV	0.5
KPI_{1A}	0.166666667
KPI_{2A}	0.041666667
KPI_{2B}	0.041666667
KPI_{2C}	0.041666667
KPI_{2D}	0.041666667
KPI_{3A}	0.166666667
C_8	0

The criterion "C_8" in Table 8 refers to the terminal criterion of the externality branch which in this case is neglected.

4.6 The pairwise comparison of the alternatives

In the case study, the fulfilment of the terminal criteria is measured by means of quantitative metrics. For each terminal criterion a preference matrix is built by means of the automatized pairwise comparison described in section **Errore. L'origine riferimento non è stata trovata.**. In the following tables the result obtained by means of the *MC-CBA toolkit* is reported. The input data are the PM in Table 6.

As shown in Table 9, the baseline alternative (A_1) is outclassed by all the other alternatives. The result obtained is in line with the economic performances of the options. According to Table 6, the alternative A_5 achieves the highest economic performance.

Table 9. Preference matrix related to the NPV criterion

Criterion VAN	A_1	A_2	A_3	A_4	A_5
A_1	1	0,111111111	0,111111111	0,111111111	0,111111111
A_2	9	1	1	1	0,5
A_3	9	1	1	1	0,5
A_4	9	1	1	1	1
A_5	9	2	2	1	1

Table 10 reports the preference matrix related to the terminal criterion KPI_{1A}. According to the performances in Table 6, the obtained preference matrix highlights that the alternative A_1 is outclassed by the other alternatives.

Table 10. Preference matrix related to the criterion KPI_{1A}

Criterion KPI_{1A}	A_1	A_2	A_3	A_4	A_5
A_1	1	0,111111111	0,111111111	0,111111111	0,111111111
A_2	9	1	1	1	1
A_3	9	1	1	1	2
A_4	9	1	1	1	1
A_5	9	1	0,5	1	1

Table 11 reports the preference matrix related to the terminal criterion KPI_{2A}. Also in this case, all the alternatives outclass the BaU alternative (A_1).

Table 11. Preference matrix related to the criterion KPI_{2A}

Criterion KPI_{2A}	A_1	A_2	A_3	A_4	A_5
A_1	1	0,111111111	0,111111111	0,111111111	0,111111111
A_2	9	1	1	1	1
A_3	9	1	1	1	2
A_4	9	1	1	1	1
A_5	9	1	0,5	1	1

Table 12 reports the preference matrix related to the terminal criterion KPI_{2B}. The preferences evaluated by the automatic pairwise comparison accords with the performances of the alternatives. The A_1 has the lowest SAIDI whereas all the other alternatives have the same value.

Table 12. Preference matrix related to the criterion KPI_{2B}

Criterion KPI_{2B}	A_1	A_2	A_3	A_4	A_5
A_1	1	0,111111111	0,111111111	0,111111111	0,111111111
A_2	9	1	1	1	1
A_3	9	1	1	1	1
A_4	9	1	1	1	1
A_5	9	1	1	1	1

Table 13 reports the preference matrix related to the terminal criterion KPI_{2C}.

Table 13. Preference matrix related to the criterion KPI_{2C}

Criterion KPI_{2C}	A_1	A_2	A_3	A_4	A_5
A_1	1	0,111111111	0,111111111	0,111111111	0,111111111
A_2	9	1	1	1	1
A_3	9	1	1	1	1
A_4	9	1	1	1	1
A_5	9	1	1	1	1

Table 14 reports the preference matrix related to the terminal criterion KPI_{2D}. Although the alternative A_5 has a lower performance than the alternatives A_2, A_3, and A_4, this slightly difference does not cause a different value of the obtained preference.

Table 14. Preference matrix related to the criterion KPI_{2D}

Criterion KPI_{2D}	A_1	A_2	A_3	A_4	A_5
A_1	1	0,111111111	0,111111111	0,111111111	0,111111111
A_2	9	1	1	1	1
A_3	9	1	1	1	1
A_4	9	1	1	1	1
A_5	9	1	1	1	1

Table 15 reports the preference matrix related to the terminal criterion KPI_{3A}. The alternative A_1 achieves the lowest performances (the highest energy losses); thus, it is outclassed by the other alternatives. The pairwise comparisons among the remaining alternatives show differentiated preferences.

Table 15. Preference matrix related to the criterion KPI_{3A}

Criterion KPI_{3A}	A_1	A_2	A_3	A_4	A_5
A_1	1	0,111111111	0,125	0,111111111	0,111111111
A_2	9	1	1	1	1
A_3	8	1	1	0,5	1
A_4	9	1	2	1	1
A_5	9	1	1	1	1

4.7 Result of the *MC-CBA toolkit* evaluation

4.7.1 Partial result

In this section the partial result obtained by means of the *MC-CBA toolkit* is described. Table 16 reports the normalised partial scores achieved by the 5 alternatives on the two branches. Observing the partial scores, the alternative A_5 scores the highest in the economic branch, while the A_4 is the best alternative according to the smart deployment merit evaluation. A_4 is the more effective in satisfying the smart grid criterion, however, has an economic performance lower than A_5. The BaU alternative (A_1) achieves the lowest partial score in both branches.

Table 16. Partial score obtained by the alternatives

Alternative	Partial score economic branch	Partial score Smart grid branch
A_1	0.026526488	0.026983905
A_2	0.207192879	0.241141339
A_3	0.207192879	0.247484253
A_4	0.238738392	0.254851806
A_5	0.320349362	0.229538697

4.7.2 Overall score

The overall score of each alternative is evaluated by the *MC-CBA toolkit* by multiplying the matrix of the partial scores and the vector of local weights of the first level criteria. Table 17 reports the overall score obtained in the case study by considering the weights in Table 7, according to the overall scores a ranking of the alternatives is built. The alternative which achieves the highest overall score is considered as the best alternative of the set.

Table 17. Overall score

Alternative	Overall score
A_5	0.274944029
A_4	0.246795099
A_3	0.227338566
A_2	0.224167109
A_1	0.026755197

Table 17 highlights that A_5 is the best alternative of the analysed set. Conversely, the alternative A_1 is the worst. A_5 and A_4 both provide a same sized DES device, the difference on the economic performance depends on its management which yields to a different network investment cost and/or reactive power exchange. A_3 is similar to A_5, but the DES device installed in the bus 14 has a bigger size and the performance on the economic criterion is lower. Even if A_3 installs a bigger device than A_4, the performances on the smart grid deployment merit branch are lower than A_4; hence, topology and scheduling of storage strongly influence the benefits that a device produces, size is not the only key factor that has to be considered.

In Figure 7 the result of a sensitive analysis made by varying the relevance assigned to the two branches is depicted. In the case study the first level hosts only two criteria, therefore the sensitivity analysis on local weights respects the constraints (22).

$$w_{ECO} + w_{SG} = 1\ ;\ w_{ECO}, w_{SG} \in [0,1] \tag{22}$$

Where w_{ECO} and w_{SG} are the local weights of the economic and the smart grid deployment merit branch.

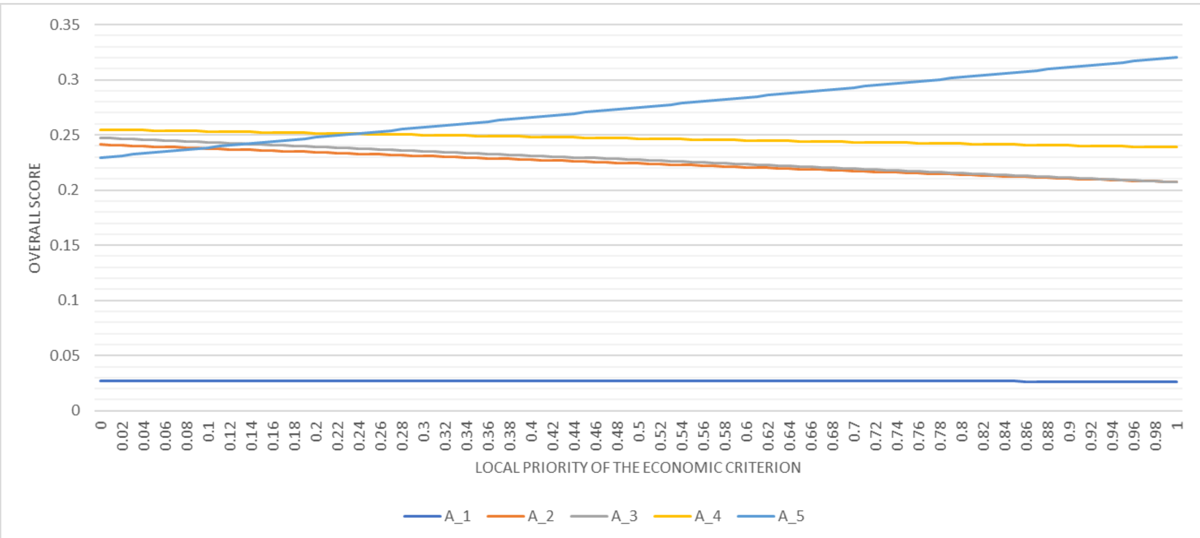

Figure 7. Sensitivity analysis on the first level criteria weight

According to partial scores, the alternatives A_4 and A_5 are the only options identified as best option in the criteria weight range. More specifically, the breakpoint is 0.24. If the economic branch has a local weight lower than 0.24 (hence the smart grid deployment merit branch has a local weight higher than 0.76), the best alternative according to the MC-CBA framework is A_4. Contrariwise, the best alternative is A_5.

As highlighted by the sensitivity analysis, even if the DES device has the same size, the bus in which it is installed influences the obtained economic and technical impacts. In the present case study, the best alternative concerns a DES device installed in the same bus where the biggest DG of the network is located. In addition, this DG is based on wind turbine while the others DG in the network are PV plants.

5 Closing discussion

This document presents the model of the *MC-CBA toolkit* which aims to support DMs in smart grid planning. The proposed approach is general purpose since it can be used for assessing any smart grid asset by identifying the relevant evaluation criteria. The aim of the proposed MC-CBA framework is to help DMs of companies and government bodies in strategic planning. By identifying the best option and by analysing the sensitivity with respect to criteria weights, the DM obtains an overview of the effects produced by each alternative. The effectiveness of complex planning problem is increased since the DM is supported by a systematic framework which simplifies the analysis and rejects personal biases. The usefulness of support decision tools, as the presented *MC-CBA toolkit*, rises together with the decision-making problem dimension. As the number of criteria and/or alternatives increases, identifying the best option become extremely difficult and burdensome. Moreover, the presented MC-CBA framework is an output-based assessment which does not require to convert all impacts in monetary terms, hence it is suitable for accounting social and technical impacts of power system planning without introducing any underlying bias.

The presented case study concerns the project selection among a set of ADN planning alternatives. As no-network solution, DES is owned and managed by the DSO for solving network contingencies. Amongst non-network planning solutions, DESs are considered as a complementary asset to the DG by relieving the intermittent behaviour of renewable energy sources. Moreover, the enhanced operational flexibility of a distribution network equipped with DES contributes to shifting the electrical power system from the load following paradigm to the generator following. If optimally allocated, DESs can provide to the DSO numerous technical and economic benefits which are not mutually exclusive; a single storage device can offer different services. Therefore, to understand the multiplicity of benefits is necessary to analyse DESs planning alternatives through a multi-criteria methodology. An approach focused on a single benefit or application cannot be effective to get the best planning alternative since the other capabilities could be disregarded.

In the case study the alternatives are assessed according to their economic and technical impacts. The result highlights that the alternative identified as the best of the set represent a compromise between the two area of interest. The sensitivity analysis reveals the breakpoints of the result and it shows how the best solution changes if the relevance of the areas of interest changes. Moreover, it underlines the responsibility of the DM who has to carefully identify the weights of the assessment in order to represent properly the stakeholders' view.

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