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Towards an Inclusive, Safe, Resilient and Sustainable City: Approaches and Tools

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Indice/Index

USING LINGUISTIC DESCRIPTIONS WITH MULTI-CRITERIA DECISION AID APPROACHES IN URBAN ENERGY SYSTEMS

Arayeh Afsordegan, Mónica Sánchez, Núria Agell, Gonzalo Gamboa, Lázaro V. Cremades

Abstract

Multi-Criteria Decision Aid (MCDA) methods include various collections of mathematical techniques related to decision support systems in non-deterministic environments to support such applications as facility management, disaster management and urban planning. This paper applies MCDA approaches based on qualitative reasoning techniques with linguistic labels assessment. The aim of this method is ranking multi-attribute alternatives in group decision-making with qualitative labels. Finally this method is applied to a case of urban planning in selection of the less energy consumption project in a geographical area in Catalonia.

Keywords: Multi-Criteria Decision Aid, qualitative labels, energy

LE DESCRIZIONI LINGUISTICHE NEGLI APPROCCI MULTICRITERIO DI AIUTO ALLA DECISIONE (MCDA) PER LA VALUTAZIONE DEI SISTEMI DI PIANIFICAZIONE ENERGETICA

Sommario

I metodi multicriterio di aiuto alla decisione includono diverse tecniche matematiche relative ai sistemi di supporto alle decisioni in ambienti non-deterministici per facilitare la gestione dei servizi, la gestione delle catastrofi e la pianificazione urbana. Questo articolo applica due approcci multicriterio basati sulla combinazione di tecniche qualitative con la valutazione di descrizioni linguistiche. Lo scopo è quello di classificare le alternative multi-attributo in processi decisionali di gruppo con descrizioni qualitative. Il metodo è stato applicato ad un caso di panificazione urbana per la selezione del progetto con il minor consumo energetico in un'area geografica della Catalogna.

Parole chiave: MCDA, descrizioni qualitative, energia

1. Introduction

Multi-Criteria Decision Aid (MCDA) approaches under uncertainty and fuzzy systems are accepted as suitable techniques to deal with conflicting problems and in particular in energy analysis and planning. The sustainable energy planning include different variables, as the decision making is directly related to the management of different type of information with different aspects such as technological, environmental, economic and social. MCDA methods include various collections of mathematical techniques related to decision support systems in non-deterministic environments to support such applications as facility management, disaster management and urban planning. (Doukas *et al.*, 2007; Figueira *et al.*, 2005; Roy and Słowiński, 2013; Słowiński and Teghem, 1990; Wang *et al.*, 2009). Urban energy systems present multiple identities with multiple criteria, which are subject to non-equivalent descriptions and the relevant aspects cannot be captured using a single perspective. For example in the case of buildings, an architect would describe the criteria in terms of volumes, shapes, materials and orientation. By contrast, sociologist would look at the people living in the building, and describe it according to demographic, cultural and socio-economic characteristics. Different persons with different backgrounds would focus on different aspects of the building according to what they consider relevant for the analysis. In order to deal with this issue, this study introduces the qualitative MCDA by using linguistic description applied to the SEMANCO (Semantic tools for carbon reduction in urban planning) project to assess the energy performance of urban plans and projects and to compare them against the baseline and against each other. In these cases, it is often difficult to obtain exact numerical values for criteria and indicators. In order to overcome this shortage, qualitative reasoning techniques integrated with MCDA, are capable of representing uncertainty, emulating skilled humans, and handling vague situations.

Frequently, this uncertainty is captured by using linguistic terms or fuzzy numbers to evaluate the set of criteria or indicators (Dubois *et al.*, 2003; Madrazo *et al.*, 2014a). Agell *et al*. (2012) proposes a qualitative reasoning technique to overcome uncertainty in human judgments that involve vague information. In a decisional process, assessment and selection of alternatives derive from complex hierarchical comparisons among them, which are often based on conflict criteria. This method can be used as a systematic tool for sustainability assessment. Several studies on energy planning have been developed to help energy planners and policy makers to design strategies for energy system models (Beccali *et al.*, 2003; Gamboa and Munda, 2007; Kaya and Kahraman, 2011; Liu, 2007; Pohekar and Ramachandran, 2004; Polatidis *et al.*, 2006; Tsoutsos *et al.*, 2009).

The aim of this paper is to analyze qualitative MCDA approaches with the distance function aggregations applied to urban energy systems. This paper considers the qualitative approach with linguistic labels for ranking multi-attribute alternatives in group decision-making. This method is applied to the real case study of the SEMANCO project to provide an appropriate energy information framework.

The paper is organized as follows: Section 2 describes some relevant MCDA methods applied to energy planning and review different policy frames for energy management. Section 3 introduces a specific MCDA method where qualitative alternatives' descriptions are considered. In Section 4, SEMANCO integrated platform application is presented in order to assess the energy performance and CO_2 emissions of projected urban plans at city level. Finally, the last section highlights some conclusions and future research directions.

2. Related works and theoretical framework

Since the 1950s and 1960s, when foundations of modern multi-criteria decision-making methods have been laid, many researches devoted their time to development of new multi-criteria decision-making models and techniques. In the past decades, research and development in the field have accelerated to continue growing exponentially. However, the methodological choices and framework for assessment of decisions are still under discussion. The general purposes of MCDA are describing trade-offs among different objectives and structuring decision process, defining and selecting alternatives, criteria and weights and finally evaluating the results to make decisions. Most of MCDA approaches which can handle both quantitative and qualitative criteria, share the common characteristics of conflict among criteria and difficulties in design or selection of alternatives (Pohekar and Ramachandran, 2004; Wang *et al.*, 2009).

A large number of multi-criteria techniques have been developed to deal with problems with different objectives such as choice, ranking and sorting or classification problems.

There are several methods base on priority, outranking, distance or mixed methods which can be applied to these problems. A decision-maker is required to choose relevant method in each problem. In the case of energy problems, multi-criteria methods should be simple to promise transparency, consider the intensity of preferences and be partially. These features are difficult to gather in one specific method simultaneously. In energy planning issue, the group of studies address to the significant potential of MCDA techniques in the urban energy systems or direct relevance to the use of energy in cities which can be found in (Blondeau *et al.*, 2002; Chang *et al.*, 2008; Dutta and Husain, 2009; Hsieh *et al.*, 2004; Keirstead *et al.*, 2012; Medineckiene *et al.*, 2014; Mosadeghi *et al.*, 2015; Qin *et al.*, 2008; Wang *et al.*, 2014; Wright *et al.*, 2002; Zavadskas and Antuchevičiene, 2004; Zavadskas and Antucheviciene, 2006).

Among all categorization in MCDA, reference point and outranking methods are widely used in the case of ranking problems (Beccali *et al.*, 2003; Loken, 2007). The study of ranking process is considered as a interest issue by computer science and artificial intelligence in the field of decision making, learning and reasoning (Belton and Stewart, 2002; Zadeh, 2001). In this case, one of the active subfield of research in artificial intelligence is Qualitative Reasoning (QR) which tries to understand and explain human beings' ability to reason without having exact information. The main objective of QR is to develop systems that permit operating in conditions of insufficient or without numerical data. Most of the selection elements cannot be given precisely and the evaluation data of the suitability of alternatives for subjective criteria are usually expressed in linguistic terms by the decision-makers preferences. There exist many different representation formats that can be used in each model, i.e., preference orderings, utility values, multiplicative preference relations and fuzzy preference relations among others.

Qualitative reasoning is able to reason at a qualitative or symbolic level directly in terms of orders-of-magnitude. To represent non-trivial domain knowledge, the patterns or alternatives to be ranked are characterized by a set of features, which are evaluated by each actor through linguistic labels corresponding to ordinal values.

Order-of-magnitude models are among the essential theoretical tools available for qualitative reasoning about real systems. They aim to capture order-of-magnitude commonsense inferences, as used by human beings in the real world. A general qualitative algebra structure was defined on the absolute order-of-magnitude model, providing a mathematical foundation unifying sign algebra and interval algebra through a continuum of qualitative structures built from the roughest to the finest partition of the real line. Specifically, the one-dimensional absolute order-of-magnitude model works with a finite number of qualitative labels corresponding to an ordinal scale of measurement (Travé-Massuyès *et al.*, 2005).

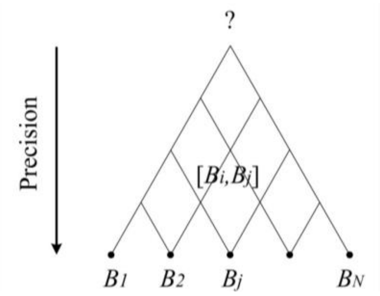
Techniques based on order-of-magnitude qualitative reasoning have provided theoretical models that can obtain results from non-numeric variables. The main advantage of this method is the capability to deal with problems in such a way that the principle of relevance is preserved, that is, each variable is valued with the level of precision required. Other advantage is that it tackles the problem of integrating the representation of existing uncertainty within the group (Forbus, 1984). In the following section we are going to introduce the algorithm description of the method in this framework.

3. A Multi-Criteria Decision Aid method

Agell et al. introduced in 2012 a qualitative approach for ranking alternatives motivated by the Reference Point Method which ranks the alternatives by using a distance function defined on the absolute order-of-magnitude qualitative space. This technique uses qualitative assessments of alternatives and minimizes the distance between them and a certain target point that models the best performance for each criterion considered. It deals with the problem in such a way that the principle of relevance is preserved. Depends on the features of each variable, the number of labels chosen to describe a real problem is not fixed.

In this method, the absolute order-of-magnitude qualitative space is used for the process of moving from the ordinal scale of the original data set to a cardinal scale by codifying the labels using location function. The space of k-dimensional vectors of labels, being k the product of the number of experts (m) by the number of criteria (r), allows the representation of alternatives from linguistic evaluations of experts by basic or non-basic labels with different granularity (Fig. 1). The basic labels, corresponding to linguistic terms, are defined by a discretization given by a set $\{a_1, \ldots, n\}$ of real numbers as landmarks, $B_i = [a_i, a_{i+1}]$ (where i= 1, …, n). The non-basic labels describing different levels of precision, are defined as $[B_i, B_j] = [a_i, a_{i+1}]$ (where i= 1, …, n).

Fig. 1 – Labels with different granularity



Source: Agell et al. (2012)

A location function introduced as an element in $\Re^2$ is defined by the addition of measures of basic label to its right and to its left (Formula 1):

$$l\left(\left[B_i, B_j\right]\right) = \left(-(i-1), n-j\right) \tag{1}$$

This function codifies each alternative via a 2-k dimensional vector of integer numbers. The vector (B_n, …, B_n) is considered as a reference label to compute distances. The location function is applied to each component of the k-dimensional vector of labels representing an alternative. As a result, each alternative is codified via a vector in $\Re^{2k}$. In order to rank the alternatives, the Euclidean distance of each alternative to this reference vector with respect to different criteria is computed. Finally alternatives are ranked according to their minimum distance to the reference label (Formula 2):

$$d\left(A, A\right) = \sqrt{\sum_{i=1}^{r} w_i (\sum_{j=1}^{2m} (X_{ji} - X_{ji})^2} \tag{2}$$

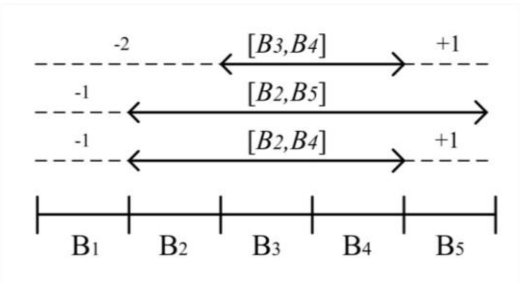
where w_i is the weight corresponding to each indicator.
Let us consider the absolute order-of-magnitude model with granularity 5 from strongly agree to strongly disagree, see Table 1.

Table 1 – Linguistic label description

Basic labels	**Linguistic labels**
B_1	Strongly disagree
B_2	Disagree
B_3	Neither agree nor disagree
B_4	Agree
B_5	Strongly agree

Each linguistic label corresponds to a location. For instance, the location of the non-basic label of [B_2, B_4] is the pair (–1, 1) and the reference point is B_5 defined by (–4, 0), see Fig. 2.

Fig. 2 – Locations



The following section presents one of the challenging applications and domains in which the method presented has been used in the urban energy planning area.

4. SEMANCO Integrated Platform Application

Energy is a significant factor for economic development of countries. As economy advances and human society requires more energy, the problem of reducing CO_2 emissions in cities has given rise to a serious contradiction among energy supply, environment protection and economic development. It is necessary to change the energy structure, integrating new models and modifying the way we use energy such as improving the energy efficiency of buildings by means of an urban energy system model.

The building sector has significant impacts on communities. At the same time, it is the sector with the highest cost and environmental saving potentials provided effective strategies are implemented.

Buildings are responsible for 33% of worldwide energy-related GHG emissions; also it has been identified as a sector where huge savings can be made. For example, of the 40% of energy consumed by buildings in the European Union (EU), estimates reveal that the implementation of energy-efficiency measures could lead to cost-saving of around 28% (Ekins and Lees, 2008). Therefore, the built environment is arguably a sector that can play an important role in mitigating climate change impacts, reducing energy use and natural resources (Abanda *et al.*, 2013; Robert and Kummert, 2012).

So, it is not a mistake that in small and big cities sustainability practitioners focus their attention on improving building performance.

In the SEMANCO project, semantic technologies have been used to create models of urban energy systems able to assess the energy performance of an urban area to make informed decisions about how to reduce CO_2 emissions in cities. The goal of the SEMANCO research project is to create a comprehensive framework in which semantic energy information brings the data sources at different scales from different domains.

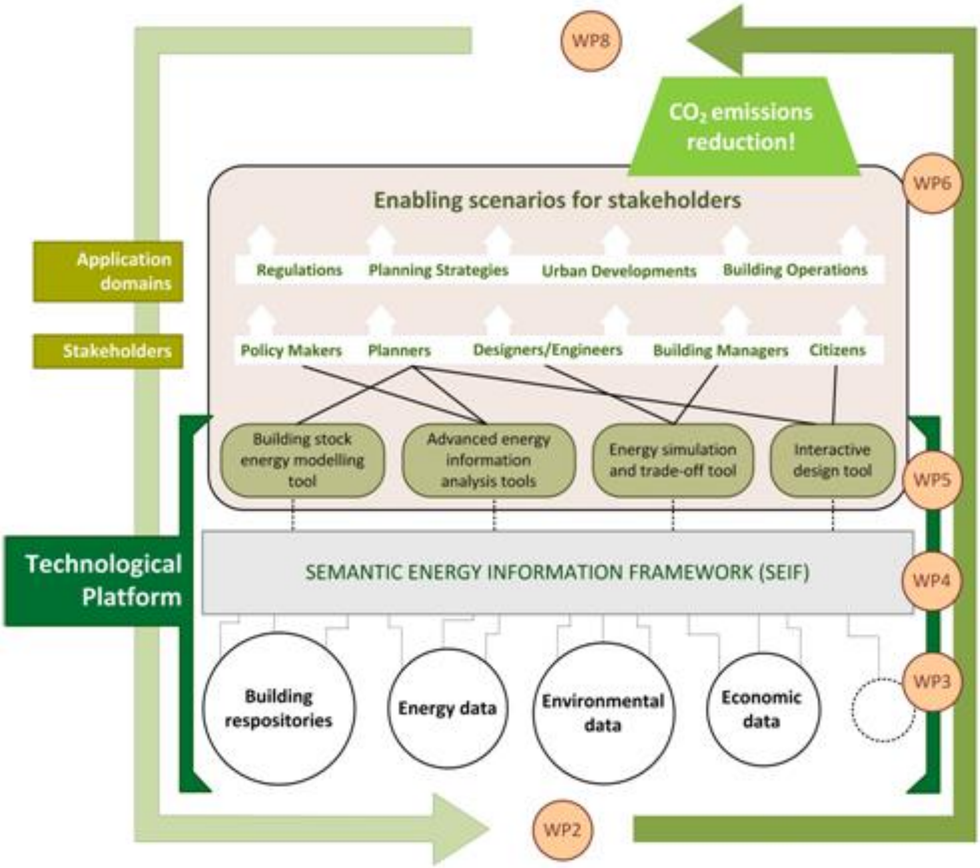
This integration of data from multiple sources with different tools is handled by a Semantic Energy Information Framework (SEIF), a key technological component developed in the project (Madrazo *et al.*, 2014a). This framework is the connection between the different data sources and the tools which use the semantically modeled data (Fig. 3).

In the integrated platform, the experts' knowledge is captured through the use case methodology, as well as the links to the external data sources which are available via the SEIF. This combination of knowledge and information constitutes the base for creating energy models for a specific urban area.

Ontology can be used to create shared vocabularies which help experts from different fields to establish relationships between certain objects of an urban energy system according to their knowledge and experience (Gruber, 1992). It can serve to promote communication between the semantically modeled data and the various software applications used by experts. This ontology has been applied to three case studies in the SEMANCO project, first at the building scale and later on at the urban level.

Different scenarios located in Copenhagen (Denmark), Manresa (Spain) and the Newcastle (United Kingdom) will enable defining the scope of the research and outlining the specifications for the tools needed by stakeholders in different domains (Fig. 4). Use cases defined by means of these templates are a foundation in the ontology building process.

Fig. 3 – Structure of SEMANCO project



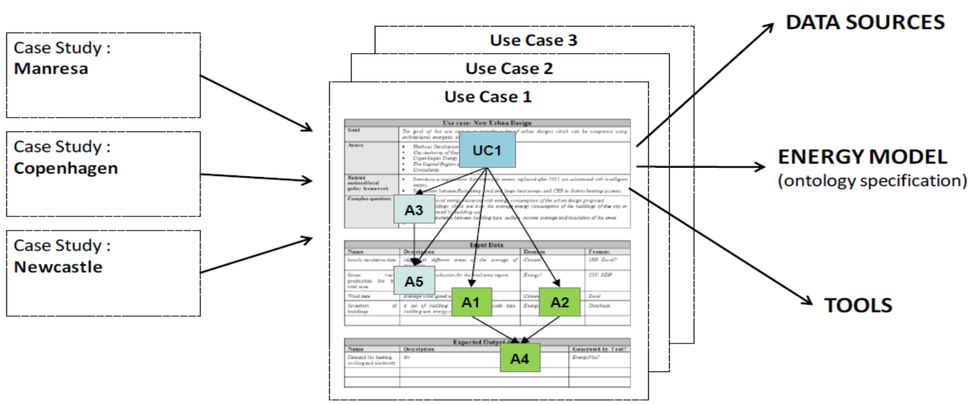
Source: Madrazo et al. (2012)

The platform shown in Fig. 5 has been designed to support services for different user groups. Real energy and different information such as socio-economic information can be obtained before and after implementation of some actions. The description of building typologies will consider the energy carriers used and final use within the building in building and neighborhood levels.

Experts can represent the existing conditions of the urban system (*descriptive model*), analyze the future evolution of the system (*predictive model*), explore different scenarios for future development (*exploratory model*) and propose improvement plans and evaluate projects to improve the performance of the urban energy system (*planning model*) using multi-criteria decision aid tools (Madrazo *et al.*, 2014b).

The MCDA tool compares alternatives in order to decide which improvements might be most suitable by generating a new plan. Figure 6 shows that each plan has a set of project attached to consider the effect of different interventions for example window improvement, heating system improvement, roof isolation and adding renewable thermal energy supply. The user can switch back to the plan interface and use the multi-criteria tool developed to compare the interventions contained within each project. This helps them decide which project they would prefer to enact in practice.

Fig. 4 – Structure of SEMANCO project

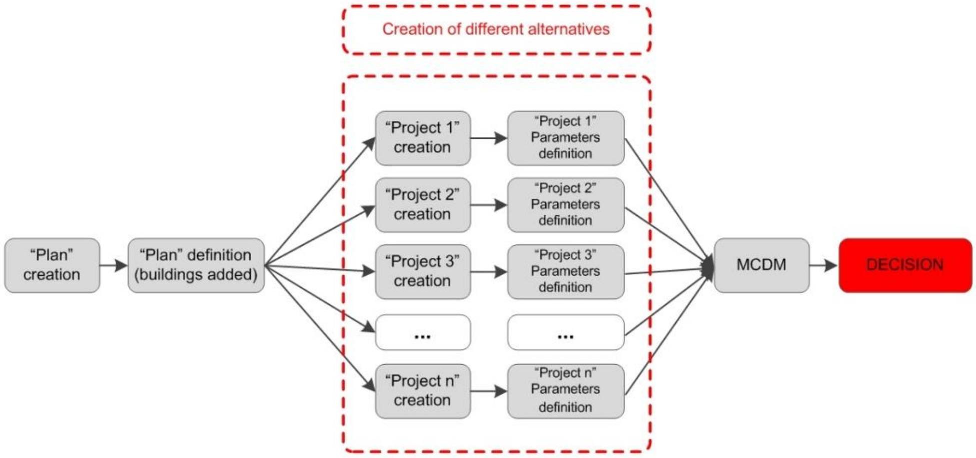


Source: Madrazo et al. (2012)

Fig. 5 – Integrated Platform and Building selection in the platform interface

Source: Madrazo et al. (2014b)

Fig. 6 – Workflow for decision making within the platform



Source: Carpenter et al. (2014)

In order to illustrate the use of the MCDA tool within the SEMANCO integrated platform, Let us consider a case where a plan has been created to refit the set of buildings and three projects proposing different ways of doing this have been created. The basic results from these can be seen in the following section.

5. Results

In this section, the results provided by qualitative MCDA applied to SEMANCO platform are presented. Indicators are crucial components in the overall assessment of progress towards sustainable development. In this study, the indicators shown in Table 2 are considered according to the calculation methods and input indeeds. On the other hand, two qualitative criteria which are ease of implementation and social acceptability are also considered to use the advantage of expert`s assessment by means of qualitative MCDA approach.

According to the given relative importance via experts, different possible improvement types (such as solar PV, heat pumps and extra insulation) for each of these indicators are defined as Project A, Project B and Project C beside the baseline (current plan), which is denoted by the plan's name Policy change, is also considered in the analysis (Fig. 7). The calculated baseline will be a reference to assess the effectiveness of the improvement plans developed for the last round of demonstration scenarios.

The steps of the qualitative MCDA algorithm, mentioned in Section 3, are executed. To this end, the highest score of each criterion are respectively considered as the reference label of the qualitative space. Table 3 shows these qualitative labels together with their locations, obtained directly from Equation 1.

Table 2 – Relevant indicators

Indicators	Unit	Calculation method	Input needed
Energy demand heating	kWh/year	kWh/year = kWh/m^2 * total number of m^2 (differentiating between households and office buildings)	The total annual consumption of energy spend on heating per m^2 for households and office buildings is needed to find this indicator along with the number of m^2 in households and office buildings in the scenario.
CO_2 emission	gCO_2/MJ	Average CO_2 – factor for heat (gCO_2e/GJ) = (heat supply from grid (GJ)*CO_2 – factor heat-grid gCO2e/kWh) + Heat production in city district (GJ)*CO_2 factor city heating (gCO_2e/GJ))/[heat supply from grid (GJ) + Heat production in city district (GJ)]	Input needed is CO_2 emission-factors for heat produced, the total heat produced and total heat consumed, all within the city district, along with CO_2 emission-factors for heat produced outside the city district.
Heating cost	€/MJ	The price per kWh for the chosen heat supply solution is calculated on the basis of the combined investment costs, net present value of the operating costs over a 20 year period, including subsidies in the period in relation to the expected production. Efficient heat supply solutions could be: Conversion from natural gas to district heating. CHP based on biomass Low temperature areas. Efficient utilization of the temperatures in the district heating grid.	The total cost of supplying heat (investments, running costs, profit margin, etc.) and the total amount of heat produced from different sources.

Source: Niwas et al. (2012)

Table 3 – Different indicators with different granularity

Indicators	Granularity	Reference label locations
Energy demand heating	$(B_1, \ldots, B_{10})$	(-9,0)
CO_2 emission	$(B_1, \ldots, B_8)$	(-7,0)
Heating cost	$(B_1, \ldots, B_5)$	(-4,0)
Ease of implementation	$(B_1, \ldots, B_7)$	(-6,0)
Social acceptability	$(B_1, \ldots, B_7)$	(-6,0)

Fig. 7- New plan sample platform

The first step of this algorithm is assigning qualitative labels to the quantitative scores to simplify the computation in the process of ranking. The qualitative MCDA approach considered in this example uses different basic qualitative labels with different granularity for each criterion which corresponds to several intervals whose length is defined via the distance of minimum and maximum scores (see Table 4). Then, the Euclidean distance of each alternative from two reference labels is calculated by means of Formula 2. Finally, these values are combined to give a single ranking for each improvement type. The intention is not that the output from this tool should be followed in an absolute manner but rather that it should serve to aid decision makers by clarifying their intentions. Table 5 shows the values of the distance of each alternative to the reference labels. According to the minimum distance values, the following ranking is presented: Project C > Project B > Baseline > Project A.

Table 4 – Basic linguistic labels

	Weights	Policy change	Project A	Project B	Project C
Energy demand heating	1/9	B_5	B_1	B_6	B_7
CO_2 emission	3/9	B_4	B_1	B_5	B_6
Heating cost	2/9	B_3	B_1	B_3	B_4
Ease of implementation	2/9	B_3	B_1	B_6	B_4
Social acceptability	1/9	B_3	B_4	B_3	B_2

Table 5 – Distances aggregation

Alternatives	d_i^*
Policy changes	5.34
Project A	8.70
Project B	3.9
Project C	3.82

On the basis of the current plan, Project C is better in all indicators except social acceptability which has a minimum importance among other indicators. In the comparison of best options, project C is a winner in quantitative indicators and project B in qualitative ones. So, being the weights of qualitative indicators more important can cause a ranking reversal between these two options.
The method uses for ranking these projects, does not require the handling of the previous discretization or definition of landmarks to define initial qualitative terms because the calculations are performed directly with the labels so the computations are very fast and easy. Table 6 shows the features of qualitative MCDA method.

Table 6 – MCDA ranking method features

Features	Qualitative MCDA
Final Scale	Qualitative labels
Granularity	Multi-granularity
Normalization	Not requiered
Weights	Trade-off
Aggregation step	Distance function
Aggregation function	Distance to the maximum

Additionally, the qualitative MCDA method can address different levels of precision, from the basic labels, which represent the most precise ones to the least precise label which can be used to represent unknown values. So, it is possible to guarantee transparency and the intensity of preferences is considered.

6. Conclusion and future work

The proposed qualitative MCDA approaches are applied to the urban energy system to help policy makers and users in choosing appropriate decisions.
Energy consumption in cities has attracted significant research in recent years. Integrated platforms, as the one considered in this paper, provide an appropriate information framework for energy planners. The case study analyzed by SEMANCO project provides access to semantically modeled energy-related data. This access is crucial for the cities decision makers to analyze and reduce carbon emission in their cities.

The study of qualitative MCDA approach using linguistic description for preference aggregations modeling in energy planning has been performed. To do so, the qualitative approach with linguistic labels introduced by Agell *et al*. (2012) for ranking multi-attribute alternatives in group decision making is considered. In the paper it is shown that the qualitative method gives the experts the ability of dealing with uncertainty, establishes an appropriate evaluation framework for group decision-making and allows considering the intensity of preferences in decision aid. However, it has been pointed out that the feature of compensation is a shortage of this method in problems where the disadvantage of one indicator cannot be compensated by the advantage of another. As future research, the role of the weights of indicators will be studied. In addition, a real case study will be performed in the city of Manresa in Catalonia, considering data gathered in SEMANCO project.

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