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Decision Support

Measuring systems sustainability with multi-criteria methods: A critical review

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ABSTRACT

Determining the sustainability of a system (e.g. through a criteria and indicators approach) has been the focus of research in many branches of science. Frequently, this research used multiple criteria decision making techniques. In this work, we analyze and critically assess the literature published on these topics. For this purpose, a set of 271 papers appearing in the ISI Web of Science database has been studied. The results show that these techniques have been applied to a great variety of problems, levels, and sectors, related to sustainability. Thus, up to 15 multiple criteria decision making techniques, which have been applied in 4 or more papers, have been identified. Those techniques have been grouped in 5 large clusters; the two most used being those called Analytic Hierarchical Process and Weighted Arithmetic Mean. On the other hand, in this work it has been verified that the use of multiple criteria decision making techniques hybridized with group decision-making techniques is quite common, and the use of both techniques for assessing sustainability problems has risen over the last few years. The aim of this hybridization process consists of including in the analysis the preferences of the stakeholders with respect to the indicators initially suggested. Finally, it has been seen that during the past few years there has been a great proliferation of works aggregating sustainability criteria by using this type of tool, which is undoubtedly a sign of the paramount importance of these techniques in this highly pluridisciplinary context.

1. Introduction

The idea of sustainability was born in the 18th century and applied to forest management issues (von Carlowitz, 1713, in Pretzsch, 2014). However, in recent decades, its use has been generalized in extremely diverse spheres, starting from environment, agriculture, social sciences and extending to varied industrial sectors. This wide use has meant that sustainability has become a polysemous word although it has often not been used with a precise meaning. Thus, Atkisson (2006) affirms that it should not be a substitute for expressions like "*environmentalism*" or "*economic growth*". For this author, it should be seen as a "*direction for a set of criteria by which to measure our success*". Further, and putting to one side the widely extended acceptance of this word, which is incorporated into the Brundtland report, it is worth pointing out another definition of sustainability, supplied by Munier (2005) who states that "*sustainability is a process involving people, institutions, natural resources, and the environment*".

It could be said that sustainability has been dealt with from several angles, although there is a certain consensus in that it can be approached by defining an initial set of indicators. Namely, this abstract concept is specified by adequately defining a pluridisciplinary list of acceptable criteria and indicators (Raison, Brown, & Flinn, 2001). On the other hand, as multidimensionality is intrinsic to the sustainability concept, many works have attempted to characterize this term by falling back on multi-criteria techniques (from now on the acronym MCDM (Multiple Criteria Decision Making) will be associated with the word "multi-criteria"). Some authors claim that this methodology is appropriate, either for being a set of techniques which has demonstrated its usefulness in diverse environmental and management problems (Munda, 2008), or for being highly suitable when we have to select the best alternative between a discrete set of them (De Felice & Petrillo, 2013). In short, it can be said that sustainability assessment is an MCDM problem (Janeiro & Patel, 2015), since it looks for compromise solutions among conflicting criteria and indicators. Finally, in this

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manuscript, the scientific orientation of MCDM provided by the International Society on Multiple Criteria Decision Making has been followed, although other authors employ this acronym from a different perspective.

A review of the literature revealed several works in which different surveys were taken on the sustainability theme, where MCDM techniques were resorted to in one way or another. However, very few focused on making a critique of the different MCDM methods used for this task in different fields. On the contrary, it was more usual to center the review exercise on a precise orientation. Thus, some works simply reviewed the different MCDM techniques in general, such as in Azapagic and Perdan (2005b), who described 19 of them, while others concentrated on the application of MCDM techniques to a specific sector (Lai, Lundie, & Ashbolt, 2008; Pohekar & Ramachandran, 2004). On these lines, Rowley, Peters, Lundie, and Moore (2012) explained the implications of choosing an MCDM technique, dividing these into two large groups (type one and type two), clearly oriented towards discrete problems. As well as not being an exhaustive compilation of these techniques, applications to life cycle assessment (LCA) were highlighted. Another work on these lines is that of Cinelli, Coles, and Kirwan (2014). These authors were right in affirming that very rarely were the reasons leading to the selection of one technique over another justified. In their analysis they concentrated on five MDCM methods: Multi Attribute Utility Theory (MAUT), Analytical Hierarchy Process (AHP), Elimination and Choice Translating Algorithm (ELECTRE), and Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) and Dominance Based Rough Set Approach (DRSA), basing themselves on a series of conditions which those methods should satisfy with the aim of their being employed to tackle the sustainability problem. Ibáñez-Forés, Bovea, and Pérez-Belis (2014) analyzed over 70 works which used MCDM techniques in some particular sectors, dividing them into eight groups: Outranking Methods, MAUT, Fuzzy Set Methodologies, Multi-Objective Mathematical Programing, Distance-to-target Approach, Elementary aggregation methods, Complex aggregation methods and Direct ranking. Also, Wang, Jing, Zhang, and Zhao (2009) studied nine MCDM methods (Weighted sum method, Weighted product method, AHP, TOPSIS, Grey relation method, MCDA combined fuzzy methodology, ELECTRE and PROMETHEE), differentiating those used to obtain weights from each criterion, while Herva and Roca (2013) analyzed the applicability of MDCM techniques in different areas. They were grouped into three different categories (MAUT, Outranking Methods and fuzzy MCDM). Finally, other recent reviews that partly approached MCDM methods and sustainability were Arce, Saavedra, Míguez, and Granada (2015), Jato-Espino, Castillo-Lopez, Rodriguez-Hernandez, and Canteras-Jordana (2014) and Govindan, Rajendran, Sarkis, and Murugesan (2015).

Other authors only mentioned the application of MCDM techniques for tackling sustainability issues for a specific environmental problem. Thus, Lai et al. (2008) targeted urban water, Sadok, Angevin, Bergez, Bockstaller, Colomb, and Guichard (2008) agricultural systems, Ibáñez-Forés et al. (2014) several industrial sectors, Oltean-Dumbrava, Watts, and Miah (2013) transport noise reduction devices or Shmelev and van den Bergh (2016) aspects related to energy. In addition, Halog and Manik (2011) and Rowley et al. (2012) centered on sustainability problems in LCA using these methodologies. Finally, other authors compare MCDM techniques to other diverse approaches to solve sustainability problems. Thus, Brunner and Starkl (2004) analyzed a large set of techniques, which they called decision support methodology (DSM), and tested their applicability in sustainability issues. Most of these techniques were MCDMs but they co-existed with others like cost-benefit analysis (CBA), while Özdemir, Härdtlein, Jenssen, Zech, and Eltrop (2011) analyzed sustainability problems by using, besides MCDM, the following three techniques: social cost analysis, ecological footprint analysis and the exergy approach.

In synthesis, in spite of the studies mentioned above, there is no review considering sustainability questions that explain systematically the different MCDM techniques, that does not concentrate on a single sector and that analyzes other aspects related to sustainability and MCDM methods, which appear in the manuscripts analyzed. Thus, we have considered methodological characteristics: number of criteria and indicators, normalization or the main economic activities related to the different case studies. For that reason, the main objective of this work was to review the MCDM techniques employed for the aggregation of sustainability indicators and/or criteria. Basically, and starting from a wide sample of works which comprise a broad view of MCDM techniques, it was attempted to reply to questions about which techniques were being employed with the greatest frequency. Another sub-objective was to analyze the application of Group Decision Making (GDM) techniques, jointly with MCDM ones, to address sustainability issues. Finally, particular aspects on the employment of sustainability indicators and their relationship with these techniques were also considered. Summarizing, this study present the following strengths:

- It represents a comprehensive state-of-the-art of wide and current interest: the increasing use of the different MCDM approaches in the sustainability field. It seems clear that the information compiled in the paper might be useful for researchers and practitioners in the broad field of management with a sustainable orientation.
- The paper is not only a literature review on MCDM and Sustainability, but also a critical exercise of the advantages and disadvantages of the different approaches within the MCDM paradigm, when they have been used in the studied field.

The work is structured in the following way: in the next section the characteristics of the works analyzed are described, as well as the fields studied in each one. Next, a brief summary is made of the MCDM methods analyzed in order to describe the results obtained with this review. The work ends with a section devoted to discussion and conclusions.

2. Material and methods

The search for papers to include in this review focused on journals incorporated in Journal Citation Reports, (JCR) (Thomson Reuters, 2015) until October, 2015. No non-JCR journals, books or book chapters were considered. As a first step, a series of searches was made in the JCR and SCOPUS (Elsevier, 2015) databases especially in the following fields: sustainability + multi-criteria; multi-criteria + sustainability + indicators; composite indicator + sustainability; multi-criteria + indicators, aggregation + sustainability + indicators; sustainability + survey (TITLE), sustainability + review (TITLE). Also, we conducted a search in SCOPUS database with the word “sustainability” in the title, examining the 600 papers most cited and all the papers published in journals belonging to specific areas such as “decision sciences” or “economy”. We revised the papers most cited (400) which had the expressions “composite index” or “synthetic index” in the keywords. With all these data (more than 2000 papers, including repeated items) we manually selected the papers included in this study. In addition, two works previously found by the authors were consulted, such as, for instance, diverse papers addressing the topic of sustainability in the forestry context (Diaz-Balteiro & Romero, 2008; Diaz-Balteiro, González-Pachón, & Romero, 2013). Besides this, it is very important to note that the main objective of this study was not to conduct an exhaustive survey of all papers published regarding MCDM and sustainability. Finally, it should be emphasized that some works which constructed synthetic indices or in which different aspects unrelated to sustainability were addressed did exist. Logically, those works were not considered in our analysis. Further, in this paper no other habitual works on sustainability analyzes (OECD, 2008) were considered; for example, the selection of indicators employed in each problem or the imputation of lost values.

Once the works were localized and selected, the following step was to define a set of fields covered for all the papers analyzed. That is to say, in addition to the bibliographic data of these studies, some aspects were contemplated:

- the existence of a normalization system for the indicator values
- the number of criteria and/or indicators
- the existence of an analysis in order to discard any redundant indicators
- any sensitivity analysis applied.
- if the results were expressed spatially by means of a Geographical Information System (GIS).
- if the MCDM methodology formed part of a decision support system (DSS)
- if the uncertainty had been incorporated into the analysis (regardless of the existence or not of a sensitivity analysis).
- the existence of a GDM problem
- within a GDM scenario, it was calculated how many groups of stakeholders were considered, as well as number of diverse stakeholders, experts or analysts who were included in the analysis.
- which economic activity was associated with each paper, following the Statistical Classification of Economic Activities in the European Union (European Commission, 2015).

3. MCDM techniques

This section presents an overview characterizing the main features of the MCDM techniques dealing with sustainability issues used in the literature reviewed. It is interesting to note that GDM techniques play an important role in the problem addressed. In fact, in many situations, the problems associated with the aggregation of indicators increase due to the existence of a group of stakeholders with different perceptions or preferences with respect to the indicators considered. Throughout the presentation, the term stakeholder is used in a broad sense comprising experts or decision-makers, among others.

Regarding the presentation of multi-criteria techniques, some initial caveats should be made. First, the techniques outlined in this overview basically corresponded to those expounded in any well-known book devoted to multi-criteria analysis. In this direction, for classic references see: Cohon (1978), Steuer (1986), Yu (1985), Zeleny (1982), and for more updated works see: Figueira, Greco, and Ehrgott (2005) and Bouyssou, Marchant, Pirlot, Tsoukiàs, and Vincke (2006), among others. Second, comments and specific references about a certain technique will be made only when one technique or other has been used in the sustainability field at least in four papers. However, when the technique has been used no more than three times it appears under the generic heading of “Other MCDM Methods”. The threshold of four might look arbitrary. However, it represents a sensible compromise in order to provide a balance view of the topic analyzed.

On the other hand, the methods shown in the next paragraphs do not represent a general classification of multi-criteria techniques but are only an account of those used in the papers mentioned in this overview. First, the methods based on the minimization of distance functions appear. The basic idea underlying these methods consists of substituting the maximization of a function comprising the preferences of the DM, as a utility function, as happens in classic optimization, by the minimization of the distance existing between an alternative and a point or points enjoying good preferential properties. The distance between the alternative and the reference point or points is established in a general sense by using a family of p-metric distance functions. The differences between the methods within this general framework lie in the characterization of the point or points of reference, as well as in the value of the p-metric used. It is interesting to note that for each value of the p-metric a different structure of the DMś preferences underlies it. In what follows, some basic outlines of the main characteristics of these methods are given.

Within a Compromise Programing (CP) context the point of reference is an ideal or utopian vector defined by the optimal values of the criteria considered. The components of this vector received the name of “anchor values”. In CP two p-metrics are basically used ($p = 1$ and $p = \infty$). For $p = 1$, the average of the discrepancies between the achievement of each criterion and the respective anchor value is minimized. For $p = \infty$, the maximum discrepancy is minimized, thus obtaining the most balanced solution. Key references for CP are Yu (1973) and Zeleny (1974).

Goal Programing (GP) establishes the point of reference as a Simonian “satisficing” target, whose achievement is considered good enough by the DM. With the help of two deviation variables, one positive and one negative, the model's goals are defined. The achievement function of the GP model comprises the respective unwanted deviation variables, which have to be minimized in one way or another. Several achievement functions, with different preferential interpretations, have been proposed in the literature, such as weighted, lexicographic, minmax, etc. (see e.g., Ignizio, 1976; Jones & Tamiz, 2010; Romero, 2004, among others).

TOPSIS is the acronym of “The Technique for Order Preferences by Similarity to Ideal Solutions”. This technique was the only one within this group of distance functions that considered two reference points. One was the ideal point in the sense used by CP and the other one was the anti-ideal vector. The components of this vector represented the worst possible values achieved by the criteria involved in the analysis. This method proposes the minimization of the distance with respect to the ideal and, simultaneously, the maximization of the distance with respect to the anti-ideal. TOPSIS follows a geometric orientation and consequently the metric used is the Euclidian one (i.e., $p = 2$). Technical details of this technique can be seen in Hwang and Yoon (1981) and Yoon (1987), among others. VIKOR method, a so-called compromise ranking method, was proposed by Opricovic (1998) and introduced a multi-criteria ranking index based on a measure of closeness to the ideal solution (San Cristóbal Mateo, 2012). In short, it provided a compromise ranking between the different alternatives considered.

The Reference Point Method (RPM) establishes exogenously a good point of reference and within the philosophy underlying the metric $p = \infty$, establishes a “scalarizing function”. This function is used interactively with the stakeholders, so that after some iterations a good, efficient solution is reached (Wierzbicki, 1982,1986). It is obvious that all the methods based on distance functions have linkages, points in common, and also differences. For a critical assessment of that type of issue one can consult Romero, Tamiz, and Jones (1998).

Let us move on now to the so-called discrete methods. These methods have been designed for dealing with decision-making problems defined by a finite number of alternatives, which are evaluated according to a finite, and usually not a large, number of criteria. In this direction, first a set of methods based on the so called “outranking relationship” appears. This is quite a large group of methods which have been evolving throughout the past 40 years. The basic principle underlying these methods implies that alternative A outranks alternative B, if alternative A is at least as good as alternative B, according to the concordance and discordance concepts. The former concept quantifies to what extent for a significant number of criteria alternative A is preferred to alternative B. On the contrary, discordance quantifies to what extent there are no criteria for which alternative B is much better than alternative A. Once the thresholds for the concordance and discordance indices are established, a kernel of better alternatives is developed. Within the family of MCDM outranking methods, the two most used in general, and within a sustainability context in particular were several variants of ELECTRE (Elimination and (et) choice translating algorithm) and PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations) methods. The key reference for the former method is Roy (1968, 1991) and for the latter Brans, Vincke, and Mareschal (1986). Finally, NAIADE (Novel Approach to Imprecise Assessment and Decision Environments), is an MCDM method introduced by Munda (1995), which uses a concordance index, but, in a previous step, a pairwise comparison is needed. This method can include different forms of information (crisp, fuzzy, etc.).

The Analytic Hierarchy Process (AHP) and its natural extension the Analytic Network Process (ANP) were introduced by Saaty (1977,1980). Within this context, the DMś preferences are established by following a "pairwise" comparison format, with the help of a fundamental verbal scale. Besides this, the different criteria (indicators for a sustainability scenario) and alternatives are modeled within a hierarchical structure. The preferential weights at each level of the hierarchy are elicited from the aforementioned "pairwise" comparison matrices. In this way, a final ranking of alternatives is obtained.

Data Envelopment Analysis (DEA) is a well-known non-parametric approach that uses linear programing as an instrumental element, for the purpose of establishing a partition of a set of organizational units into two disjoint subsets: the subset containing the efficient units and the subset containing the non-efficient ones. Basically, there are two DEA orientations, one assuming constant returns to scale (Charnes, Cooper, & Rhodes, 1978) and the other assuming variable returns to scale (Banker, Charnes, & Cooper, 1984). Obviously, the application of several DEA techniques to the problem of sustainability permits one to differentiate the alternatives which are sustainable-efficient from the alternatives which are non-efficient. Interesting links between DEA and MCDM can be seen in Joro, Korhonen, and Wallenius, 1998, Stewart, 1996 and Cooper, 2005, among others. Finally, we have included in this group of techniques the papers which hybridize rough set & MCDM methods, because support both ranking and classification capabilities.

Now, a somewhat miscellaneous set of MCDM techniques applied in the sustainability field appeared. Thus, we have the Multi Utility Theory (MAUT), which attempts to attach a cardinal value (utility) to each alternative by considering simultaneously several criteria within a risk context. This type of procedure is very sound from a theoretical perspective, allowing the incorporation of non-additive preferences. However, the implementation of MAUT is generally problematic, since it requires asking the stakeholders complicated questions within the format of random lotteries. That is why, in many situations it is better to resort to a deterministic version of MAUT, such as Multi-Attribute Theory (MAVT). Thus, with this approach, the questions are posed to the stakeholders in a certainty context. Thus, questions based on random lotteries are avoided, which makes the implementation process much easier. Other methods like the Weighted Arithmetic Mean (WAM) or the Weighted Geometric Mean represent to some extent practical simplifications of the MAUT and MAVT approaches. For a rigorous treatment of MAUT, MAVT and similar approaches, it is advisable to resort to the classic book by Keeney and Raiffa (1976). A less rigorous but more accessible treatment of this type of topic can be seen in Ballestero and Romero (1998, chapter 4). Other method applied in sustainability issues is ASPID (Analysis and Synthesis of Parameters under Information Deficiency), developed by Hovanov (1996, cited in Afgan, Begic, & Kazagic, 2007). Finally, the emergence of new promising approaches like the rough set theory hybridized with MCDM are of interest. This fairly new orientation provides a useful framework for dealing with aggregation procedures for discrete problems (see Greco, Matarazzo, & Słowiński, 1999, chapter 14, 2001; Greco, Matarazzo, & Słowiński, 2001).

In another sense, the aggregation of individual preferences on mutually exclusive alternatives into a collective or social preference is the core of disciplines like social choice, group decision-making or participatory decision-making. The existence of a satisfactory aggregation procedure depends on what type of data is available for these individual preferences. The data types are classified according to how decision makers show their preferences towards the different alternatives (attributes) involved (see e.g., Herrera, Herrera-Viedma, & Chiclana, 2001). Thus, the distinction between ordinal vs. cardinal preferences, complete vs. partial preferences, or local vs., global preferences, leads to different scenarios that define specific group decision-making models (see González-Pachón & Romero, 2009).

Finally, in several of the analyzed papers, a fuzzy component was introduced. It should be remembered that Fuzzy Multi-Criteria Programing (FMCP) comprises any type of MCDM approach, for which some of the model parameters (e.g., right-hand side values, coefficients of the objective functions, etc.) are fuzzy rather than crisp numbers with a definite mathematical structure (triangular, trapezoidal, etc.). The main purpose of FMCP approaches is to introduce into the model the imprecision usually inherent in the information available (Zimmerman, 1978).

Table 1
Basic statistics.

Number of papers considered	271
Number of journals where published	119
Number of criteria included in each paper (mean)	4.2
Number of indicators included in each paper (mean)	18.9
Number of groups (mean) included where GDM analysis has been performed	4.8
Number of stakeholders (mean) in the GDM analysis	24.9
% papers considered:	
which differentiate between criteria and indicators	74.2%
with a normalization method	60.9%
use an analysis to discard redundant indicators	13.3%
address a sensitivity analysis	29.9%
use GIS to define some indicators	12.5%
are integrated in a DSS (Decision Support Systems)	12.2%
with uncertainty analysis	18.8%
which includes a GDM analysis	38.4%
use fuzzy techniques	17.0%

4. Results

In this section, some comments and clarifications about the results obtained are presented. First, it should be noted that without taking into account the general surveys, most of which have been previously cited, 271 JCR papers addressing the sustainability issue within an MCDM framework were analyzed. This collection of papers covers the period of time 1999–2015. The whole list of papers appears as Supplementary material in Appendix A. In this direction, Table 1 shows some basic features of the list.

Thus, it would seem to be of interest to highlight not only the large number of different JCR journals (119) in which the papers were published, but also the different disciplinary perspectives. In other words, the MCDM orientation in the sustainability field is of a transversal nature since it applies to several disciplinary fields as well as to very different scales of work. This fact is shown in

Table 2
Distribution of the papers included among the main economic activities.

	Economic activities	Number of papers
A	Agriculture, forestry and fishing	57
C	Manufacturing	38
D	Electricity, gas, steam and air conditioning supply	45
E	Water supply, sewerage, waste management and remediation activities	35
F	Construction	41
H	Transportation and storage	15

Source: own elaboration following the Statistical Classification of Economic Activities in the European Community (European Commission, 2015).

Table 3
Analysis of MCDM methods compiled in this review.

MCDM techniques		Number of appearances
Distance functions		55
Compromise Programing		10
Reference point		4
Goal programming		11
TOPSIS		20
VIKOR		5
Other methods		5
Discrete methods		294
Outranking		33
	ELECTRE	13
	Promethee	9
	NAIADE	6
	Other methods	5
Hierarchical		111
	AHP	93
	ANP	13
	Other methods	5
Ranking and classification methods		13
	DEA	7
	Rough sets and MCDM	4
	Other methods	2
Optimizing averages		137
	MAUT/MAVT	18
	Weighted Arithmetic Mean	89
	Geometric aggregation	4
	ASPID	8
	Other methods	18

Table 2, where the most representative main economic activities associated with these papers have been collected.

Table 3 shows the quantification of the use of the different MCDM techniques applied in the papers surveyed. The reader should note that the number of techniques applied clearly surpasses the number of papers analyzed. This seeming anomaly is due to the fact that in a significant number of papers (around 67) several multi-criteria techniques were used simultaneously. Another noteworthy issue is that the number of applications of the so called discrete methods was significantly larger than the applications based on distance functions; i.e., 291 versus 55 applications. This significant difference is likely to be due to the fact that the basic problem of aggregating indicators is in itself a multi-criteria discrete problem. On the contrary, the distance function methods deal with continuous problems. Hence, the application of this type of method in the sustainability field is not straightforward, as happens with the discrete methods, but always requires some structural adaptations. Finally, two comments: first, the two discrete methods most widely used are the AHP and the WAM; second, the distance function method with most applications reported is clearly TOPSIS.

5. Discussion

For expository purposes this section is divided into four subsections. The first one is devoted to the aspects related to the characterization of the criteria and indicators, the second analyzes the aspects related to MCDM techniques, the third concentrates on aspects related to group decision making techniques and, finally, the last one is devoted to debating whether it is possible to identify which multi-criteria technique is best suited in this field. Finally, it should be noted that the results and this discussion are dependent on the assumptions made for the search of papers explained below.

5.1. Aspects related to the characterization of the sustainability criteria and indicators

One of the first steps in a sustainability exercise consists of the selection of suitable criteria and indicators. Results shown in Table 1 clearly indicate that around 74% of the papers reported distinguished hierarchically between criteria and indicators. Not only that, but some papers even resorted to more hierarchical levels like: sub-levels, sub-criteria, etc. (e.g., Mendoza & Prahbu, 2000; Michalopoulos, Hogeveen, & Heuvelink, 2013). The average number of criteria and indicators used per application was 4.1 and 19, respectively. The indicators used were defined not only according to the three traditional pillars of sustainability: economic, social and environmental. Thus, there were, among others: technical aspects (Foxon McIlkenny Gilmour Oltean-Dumbrava Souter Ashley, 2010; Prete, Hobbs, Norman, Cano-Andrade, Fuentes, and Spakovsky, 2012), political issues (Ibáñez-Forés et al., 2014), technological issues (Afgan & Darwish, 2011), recreational and tourism components (Hiltunen, Kangas, & Pykäläinen, 2008), institutional aspects (Shmelev, and Rodríguez-Labajos, 2009), or community developments (Adrianto, Matsuda, & Sakuma, 2005).

However, the application of these methods to this problem sometimes triggers some remarkable facts. Thus, in relation to that shown in Table 1, it is important to emphasize that one basic aspect of many MCDM models, i.e. normalization, was done in a high percentage of works, although in significantly fewer than those reported by Ibáñez-Forés et al. (2014), in which 70% of the studies analyzed, also related to sustainability, did not employ any normalization, or standardization, as it is called in various works (OECD, 2008). This issue is highly relevant, since, in general, the indicators are measured in different units, so before implementing any aggregation procedure to the indicators their previous normalization is necessary. Some authors (Munda, 2005; Romero, 1991) have warned about the importance of this phase, proposing different procedures for carrying out the normalization. However, it is necessary to stress that not all the MCDM methods require a normalization system (e.g., the MAUT approach).

On the other hand, a sensitivity analysis was used in around 30% of the works, a figure very close to the one supplied by Ibáñez-Forés et al. (2014), in which it was affirmed that 31% of the works reviewed performed this type of analysis. For some authors, a sensitivity analysis should be accompanied by the application of MCDM in this field because it increases the reliability and robustness of the results obtained (Herva & Roca, 2013; OECD, 2008). It should also be taken into account that this type of analysis can be carried out in diverse phases of the process that lead us to define a sustainability problem. For example, Munda (2008) affirmed that it could be made at the level of the set of indicators, of the rule of aggregation and on the weights obtained.

In some areas it is of great importance to handle spatial issues (Shmelev & Powell, 2006). For that reason, the number of works in which a geographical information system (GIS) was used to obtain some of those indicators is significant. GIS can enhance the MCDM abilities for exploring decision situations and this integration can improve the limited capacity of GIS to manage the preferences of the stakeholders (Malczewski & Rinner, 2015). The result included in Table 1 shows that 12.5% of the papers reviewed employed a GIS to obtain the value of some indicator or other.

For some authors, using a large number of indicators made it difficult to evaluate the sustainability in a certain area (Erol, Sencer, and Sari, 2011). As an illustrative example of this fact, it can be said that 25 of the works included in Appendix A started from an initial set of over 40 indicators. Thus, several authors proposed different procedures to select or screen the set of indicators chosen initially (Maxim, 2014; Wang et al., 2009). Although one of the procedures most commonly used for this task is correlation analysis, other statistical techniques can be employed such as the principal component analysis or the factor analysis (Blancas, González, Lozano-Oyola, & Pérez, 2010b; Reisi, Aye, Rajabifard, & Ngo, 2014). As Troldborg, Heslop, and Hough (2014) appropriately affirmed, it could be that different indicators may be correlated with each other, which would imply the necessity of analysing which ones were correlated and, if that correlation is high, to come to a decision to exclude some of them (Huth, Drechsler, & Köhler, 2005; OECD, 2008). Some authors even proposed a correlation analysis in order to see which indicators had a greater influence on the sustainability ranking obtained (Egilmez, Gumus, & Kucukvar, 2015).

In another direction, it is interesting to point out that the procedures for aggregating indicators in order to deal with sustainability problems have several pros and cons, as is well reported by various authors (Gómez-Limón & Sánchez-Fernández, 2010; Reisi et al., 2014). For example, in the first of these works, one of the problems indicated was the lack of any sound statistical analysis in many of these procedures.

5.2. Aspects related to MCDM techniques

The results displayed in Table 3 show the numerous MCDM techniques employed to address sustainability aspects. To be specific, up to 15 different techniques used in four or more papers were computed. This figure showed one fact, as some authors have reported: there is no standard methodology for solving sustainability problems (Santos & Brandi, 2015). On arriving at this point, it should be noted that the objective of this work has never been to infer which MCDM technique should be used in the context being examined by us. However, some reflections in this direction have been made in Section 5.4 .

The results contained in Table 3 show how the problem can be tackled conceptually from different viewpoints within the MCDM paradigm. However, it should be noted that the discrete MCDM methods prevail and that, among them, two techniques were those most frequently used: WAM and AHP. As some authors have found (Ugwu, Kumaraswamy, & Wong, 2006), it would also seem sensible to assume that one of the methods most used is WAM for its ease in applying it, as has been shown empirically in works related to sectors like energy (Wang et al., 2009). However, some authors described the consequences that had to be considered when using this method (Munda, 2005), or matters derived from introducing dependent criteria (Rowley et al., 2012). After all, for WAM implies the implicit and questionable assumption of preferential independence among criteria/indicators, and it is well-known that the AHP approach violates the axiom of the irrelevant alternatives (i.e., the so-called rank reversal problem).

Salvado, Azevedo, Matias, and Ferreira (2015) suggested that if the different indicators were correlated, the WAM could not be applied. Further, it should be realized that its use, as other methods like AHP, signifies the existence of a compensation between its indicators. This issue leads to the classic dichotomy between weak and strong sustainability (Neumayer, 2013). Thus, in this type of paper it was assumed that the achievement of indicators of different natures could be compensated, which implies a scenario of weak sustainability. However, if this type of compensation is problematic, and consequently we face a scenario of strong sustainability, other multi-criteria methods like goal programing should be used (Blancas, Caballero, González, Lozano-Oyola, & Pérez, 2010a). In short, the non-compensatory methods are more suitable for dealing with issues related to strong sustainability and the compensatory methods more appropriate for a weak sustainability context (Roy & Słowiński, 2013).

It remains to be mentioned that in other works on the application of MCDM techniques, preference with regard to the importance of the methods most used may differ from the one shown in this work. So, Hajkowicz and Collins (2007), in a study on the application of MDCM techniques to water management problems, found that the methods most frequently employed were not the same as those included in this work. Cinelli et al. (2014) also claimed that the most popular MCDM methods in sustainability themes were AHP, MAUT, ELECTRE and PROMETHEE. Conversely, our results were consistent with some authors who reported that AHP/ANP was the multi-criteria method most applied in the past few years (Medel-González, García-Ávila, Acosta-Beltrán, & Hernández, 2013). However, in spite of its popularity, some aspects linked to its application, which may be problematic, should be clarified. Thus, some authors did not recommend applying AHP after reviewing 12 MCDM methods in a ship acquisition problem (Aspen, Sparrevik, & Fet, 2015).

It was not surprising that the MCDM and GDM models were complemented by other techniques. Thus, and without wishing to be exhaustive, works including the Monte Carlo simulation (Patel, Meesters, Uil, de Jong, Blok, and Patel, 2012; Rosén et al., 2015), the Delphi method (Li, Shi, Qureshi, Bruns, & Zhu, 2014; Roth, Hirschberg, Bauer, & Burgherr, 2009), cognitive mapping (Adrianto et al., 2005; Wolfslehner & Vacik, 2011) or the SWOT method (Strengths, Weaknesses, Opportunities and Threats) (Jalilova et al., 2012) have been mentioned.

Lastly, Fig. 1 shows the temporal evolution of the application of the different methods considered in sustainability problems during the period from 1999–2015 (papers published up to 09/30/2015). Although the works including aspects of sustainability are relatively recent (no book was published with this word in the title until 1970, according to Caradonna, 2014), our attention was drawn to their proliferation, which has occurred during the past 5 years. Indeed, around 66% of the works were published in the period from 2011–2015. If we analyze these results following the typology of the MCDM methods employed in this paper (Table 3), it can be seen how some groups of techniques present a growing trend (distance functions, hierarchical methods, and optimizing averages), unlike the other two groups of techniques shown in this work. This trend coincides with the results of Cullen (2016), who, using a bibliometric method showed a growth in publications on sustainability in some fields in the last few years. For other authors, the reason causing this important advance in sustainability publications was the decision of governments, agencies and institutions to incorporate the sustainability issue into their decision-making process (Martin, 2015).

5.3. Aspects related to GDM techniques

The connection between GDM and MCDM constitutes a highly attractive line of work (Diaz-Balteiro & Romero, 2008) and some studies even compile GDM methods applied to sustainability problems, in which some of them are MDCM techniques (Brunner & Starkl, 2004). Some authors have even coined the term “*social-multi-criteria evaluation*” to integrate both techniques into a sustainability context (Munda, 2008). According to the results shown

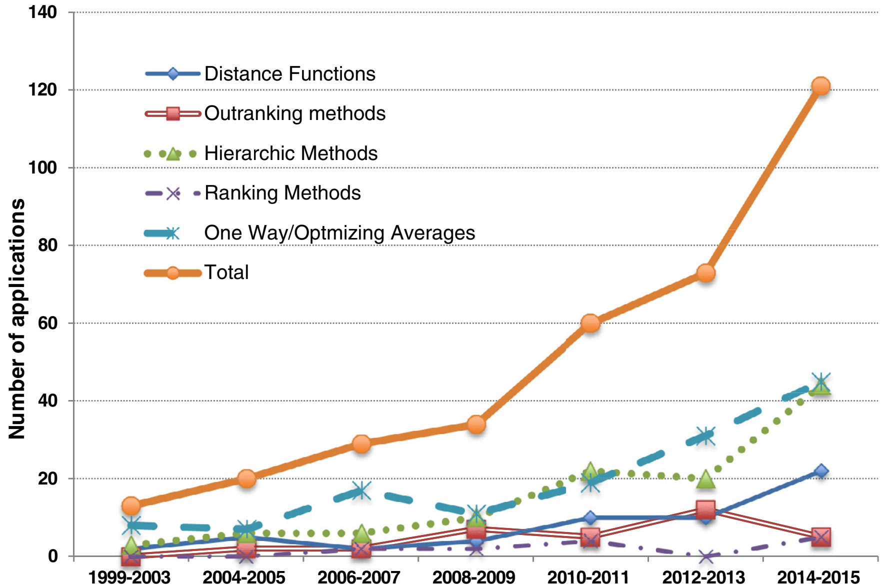

Fig. 1. Time-based evolution of the different groups of MCDM methods used in sustainability issues.

in Table 1, it is worth noting that, in a significant number of works (38.4%), a hybrid between an MCDM and a GDM model has been constructed. Furthermore, on average, they had around 5 groups of stakeholders for an average of 25 stakeholders per study. This figure may seem a high one, but for some authors it was indispensable to have a broad representation of stakeholders (Sheppard & Meitner, 2005). Finally, a recent example of merging MCDM and GDM (Borda count), using meta-indexes, was shown in Pérez, Hernández, Guerrero, León, Silva, and Caballero (2016).

These models very frequently aim to aggregate the preferences of the stakeholders for the different sustainability criteria or indicators, or, as claimed by Büyüközkan and Çifçi (2011), to reach an eventual agreement on selecting the "best" option. However, on some occasions, a limited set of archetypes or potential stakeholders has been defined instead of interviewing an extensive set of stakeholders (Hacatoglu, Dincer, & Rosen, 2015). In spite of these hybrid MCDM and GDM models, it should be pointed out that 12.2% of the works claim to have integrated these models (MDCM and GDM) into a DSS.

Finally, it should be noted that most of these GDM methods merely request the different decision-making centers to express their preferences in order to bestow weights on the different indicators without resorting to more sophisticated methodologies. Although in some cases it is said that this aggregation of preferences has certain weaknesses (Munda, Nardo, Saisana, & Srebotnjak, 2009), it would seem that these types of methodologies are commonly admitted in many fields, and many authors see them as being essential for addressing a sustainability problem evaluation (Lopez-Ridaura, Van Keulen, van Ittersum, & Leffelaar, 2005). Lastly, it can be said that it is common practice to use MCDM methods to undertake that type of aggregation of individual preferences (Diaz-Balteiro, González-Pachón, & Romero, 2009).

5.4. Choosing the best suited multi-criteria technique for sustainability measurement: some considerations

Having discussed the functioning and application of many MCDM techniques for the measurement of the sustainability associated with an alternative, it seems worthwhile to reflect on whether there is a "best" MCDM technique to be used in this field. This issue reminds one of an old question posed in classic MCDM literature: is there a best MCDM approach? Nowadays, it is well accepted that there is not now and very likely never will be a "best" MCDM technique. In fact, the main features of the problem under study will lead towards the "most suitable" approach to be used (see Ignizio, 1983 for classic discussion in this direction).

The above argument is perfectly transferable to the sustainability field. In fact, according to the characteristics of the problem under consideration, such as number of criteria, indicators or stakeholders lead to the use of one technique or another. For instance, if we are solving a problem with a small number of indicators and a reduced number of well prepared stakeholders, then why not resort to a MAUT approach? However, in the opposite situation, with a huge number of indicators and a set of stakeholders without any specific training in decision analysis, MAUT should give way to other MCDM techniques with a more pragmatic orientation like AHP, GP or techniques based on rough sets theory and outranking relationships.

On the other hand, in Fig. 2 we showed the temporal trend of the most used MCDM techniques (AHP and WAM), as well as a large percentage of the papers hybridizing MCDM techniques GDM and/or fuzzy methods. This trend related to the merging of fuzzy techniques with MCDM methods is, in general, rising (Mardani, Abbas, & Zavadskas, 2015).

On the other hand, it should be noted that whatever the MCDM technique or set of techniques used, it is essential to possess a profound knowledge of the theoretical foundations and limits of the chosen technique. In this sense, it should be noted that, in a significant number of the applications surveyed, it would seem as if the choice of the respective MCDM technique was made in a rather mechanistic way without any practical or theoretical explanation. Sometimes, it would appear that the selection of the technique was due to the familiarity of the authors with it (Cinelli et al., 2014) rather than to the theoretical or practical reasons associated with the specifications of the problem situation.

6. Conclusions

On looking at the analysis made of the application of MCDM techniques to the issue of establishing a complete ranking of alternatives in terms of aggregate sustainability, it can be concluded that this theoretical orientation has been profusely applied in a large number of areas. Furthermore, in the past 5 years, the increase has been notable. Starting from a set of 15 different MCDM

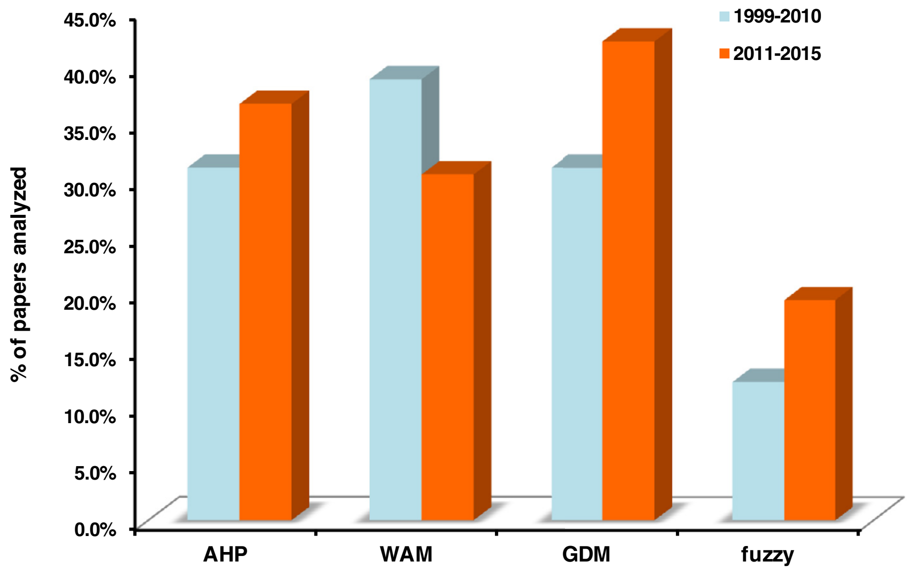

Fig. 2. Trends of the main quantitative techniques used in sustainability issues throughout the time.

techniques, the discrete MCDM methods, in accordance with the definition mentioned above, stand out as being those most frequently used. Two of them are prominent: AHP and WMA. However, this increasing trend in using these tools must not hide the fact that, on some occasions, the methodological fundamentals underlying them have been excessively slackened.

From the literature analyzed, some key issues are raised, including: some clarifications on the characterization of criteria and indicators, pros and cons of the different MCDM approaches used in practice and the strong relationship between the basic features of the problem situation and the method to be used. Even though from our analysis it is clear that there is nothing like the best suited MCDM method to be applied for any sustainable problem, our work may provide useful guidelines for researchers and practitioners in order to choose an MCDM method for dealing with a specific problem. Besides, in this work, it was verified that a high percentage of MCDM techniques were hybridized with GDM techniques in order to establish the preferences of stakeholders with respect to the indicators initially suggested, which undoubtedly enhanced the potentiality of the analysis. This trend has increased significantly in recent years. On the other hand, considering our database and the quantitative techniques proposed, research works on significant relationships between the different techniques, under different scenarios, can be put forward. For that objective, multivariate data analysis appears as being an attractive tool for a further research line. Finally, as a reviewer suggests, this study could be expanded considering that the different scales associated with the sustainability assessments can be performed at different levels (micro, meso or macro), and characterising the type of criteria/indicators selected (environmental, economic, etc.).

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Supplementary Materials

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