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Review

How Multi-Criteria Decision Analysis (MCDA) is aiding Life Cycle Assessment (LCA) in results interpretation

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ABSTRACT

Life Cycle Assessment (LCA) is a robust methodology that assesses the environmental impacts of product systems. However, assessing its outcomes is not always easy. When decision-making must be carried out in such complex situations, Multi-Criteria Decision Analysis (MCDA) may be applied. In this paper, the way in which MCDA techniques are being applied within the LCA context to aid results interpretation was assessed. The aim is to investigate the current framework of this integration and to map the application of MCDA and LCA according to the LCA steps, references and criteria. Thus, a research was made in SCOPUS and Web of Science databases through a specific set of key-words. As a result, 109 papers were identified. The survey demonstrate that MCDA is applied at three different times in LCA steps: at Life Cycle Impact Assessment (LCIA) to analyze trade-offs between impact categories, damage categories, or the LCA score with other dimensions; at the Life Cycle Inventory (LCI) step, to interpret aspects from inventory (such as waste generation); and at the Goal and Scope definition step to identify impact categories and aspects of LCI. MCDA is also used for LCIA development, to attribute significance to impact categories. In general, the Triple Bottom Line (TBL) dimension was more recurrent, followed by Environmental and Eco-efficiency (environmental-economical) dimensions. The most common criteria were global warming, acidification and eutrophication in environmental prisms, costs and profits in economic aspects and job creation and labor security in social aspects. Results have shown mutual benefits and a clear and growing interest from the scientific community in relation to MCDA/LCA. Specific subjects to be further studied are: MCDA supporting other methodological choices, such as the allocation approach; MCDA to elicit meanings for impact categories in a way to compel stakeholders and verify geographical conditions for decision-making, and; Economic and social criteria used may contribute to Life Cycle Costing and Social LCA development.

1. Introduction

Decision-making is an inherent process that is involved in everyday life, from the simplest daily things as in which clothes to wear to more complex decisions that may have long-term effects, such as buying a house. At the environmental level, where the goal is to promote sustainability, decision-making is never simple. One of the reasons why the path towards sustainable development is unclear, according to Hermann et al. (2007), is because most business contributes to a variety of interrelated environmental problems. Many authors define this interrelated-dynamic behavior, i.e. the trade-off between environmental burdens, as the core of decision-making complexity when any kind of impact assessment is held (Boufateh et al., 2011; Geldermann and Rentz, 2005; Hermann et al., 2007; Laurin et al., 2016; Le Tenó and Mareschal, 1998; Seppälä et al., 2002; Subramanian et al., 2015). At the sustainability level, this task is even more difficult. Besides the environmental aspects, sustainability must consider other dimensions. According to Drejeris and Kavolynas (2014), it is quite clear that the goal of sustainable development is to reconcile economic growth, social progress and sustainable use of natural resources, maintaining the ecological balance and ensure favorable living conditions now and in the future. Therefore, the ideal environmental decision-making must consider the triple bottom line (TBL) concept, which brings the trade-off situation to a higher level of complexity.

Other complex factors of decision-making towards sustainability are: uncertainty (Durbach and Stewart, 2012) because knowledge on these subjects is still scarce and highly subject to change in the future (Le Tenó and Mareschal, 1998); subjectivity, because personal judgment vary on which topics are most important (Le Tenó and Mareschal, 1998); and, the multi-stakeholders involvement that must be considered in ideal decision-making. Linkov et al. (2006) already emphasized this necessity when they affirmed that "no matter the context, stakeholder involvement is increasingly recognized as being an essential element of successful environmental decision making". Thus, it is no coincidence that a real and substantial application of

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sustainability through the measurement and comparability of results, in a way that satisfies the principles of sustainability of all the stakeholders is the biggest challenge for most organizations (Petrillo et al., 2016).

Related to the uncertainty due to a lack of knowledge, many tools were developed in order to bring more clarity on how sustainability aspects can be measured in the past few years. However, Duic et al. (2015) indicates that there is still “a need for improvements and new developments in the conceptual, legal and methodological frameworks to facilitate the penetration of sustainability thinking into various system scales”. Authors emphasize that this task should essentially include the development of scientific foundations for the correct setting of boundaries of sustainability systems, enabling effective implementation of advanced models for system analysis and decision support. This kind of support, to aid decision makers to perform better choices in such complex situations can be reached by methods of decision analysis (Basson and Petrie, 2007; De Montis et al., 2000; Huang et al., 2011; Ness et al., 2007; Seppälä et al., 2002).

Regarding tools that aid this process, perhaps the most important and popular are those that form the Multi-Criteria Decision Analysis (MCDA) group (Sinclair, 2011). MCDA is defined by Linkov and Moberg (2012) and Doumpos and Zopounidis (2004), as a set of tools and approaches that provides mathematical methodology that incorporates the values of decision makers and stakeholders, as well as technical information, to select the best solution or provide a classification of alternatives for a specific problem. The reason that they facilitate decision-making as a whole (Shields et al., 2011) lies on the ability to analyze these different alternatives, with conflicting criteria (i.e. the aforementioned trade-offs) and affected by various stakeholders (Manzardo et al., 2014; Myllyviita et al., 2012) in a transparent manner (Jeswani et al., 2010; Huang et al., 2011; Linkov and Moberg, 2012; Roth et al., 2009). For those aspects, MCDA is strongly indicated for environmental decision-making and it is especially useful when different social, economic, and environmental indicators are compared (Dias and Domingues, 2014; Motuziene et al., 2016; Myllyviita et al., 2014).

Myllyviita et al. (2016) indicate that MCDA has the greatest potential to be successfully applied to support sustainability assessment, but solely applying MCDA is not suggested, since it needs input from other tools and methods in order to have reliable assessments. Accordingly, Ramanujan et al. (2014) affirms that a MCDA framework should be based on quantitative measurements of a product's performance so as to instill a proactive approach. Illustratively, a general framework on how decision-making is being made is presented in Fig. 1, considering all important facets of sustainability plus technical criteria (for feasibility assessment). Generally, different scenarios or alternatives are compared for those criteria, and different methodologies/tools may be applied for a more robust quantification of scenario performance under such criteria. Some examples are presented in the flowchart, as Risk Analysis (RA), Life Cycle Assessment (LCA), Life Cycle Costing (LCC), Cost-Benefit Analysis (CBA), Health Impact Assessment (HIA) and Environmental Impact Assessment (EIA). The final step is the decision made by stakeholders, where the different scenarios are compared according to different criteria performances, a task facilitated by the MCDA approach.

It is clear that MCDA is benefited by consolidated quantitative-based methodologies. Regarding all tools and methodologies to measure a products performance shown in Fig. 1, LCA is one of the most preeminent. It is considered a robust method to assess systems and products (Guinée et al., 2002; Von Doderer and Kleynhans, 2014) recurrently used to evaluate decision alternatives (e.g. products, sites, projects) on the basis of various environmental indicators (Boufateh et al., 2011; Rowley et al., 2012). In effect, the integration of MCDA with LCA could be a practical solution (De Souza et al., 2016) to facilitate interpretation of results and to aid decision-making. LCA is a methodology, grounded in the Life Cycle Thinking (LCT) concept, which allows one to assess environmental impacts of a product or a service from cradle to grave and analyze the situation from a multidimensional perspective (Castellini et al., 2012; Myllyviita et al., 2012). The relation between MCDA and LCA may be made in two ways as discussed in the following sections of this paper.

2. MCDA and LCA

The first aspect to be highlighted to understand the relation between these two methodologies is the core essence of both, i.e., they are both decision-making aiding tools. For instance, impact indicators and criteria cover the same notion respectively from the LCA and the MCDA point of view (Le Tenó and Mareschal, 1998). The difference is that LCA quantifies its impact indicators whereas MCDA often needs to be feed by criteria (interpretation-oriented only). This statement is clear regarding its applicability. The former is directed to products and services and it is based on the compilation of the inputs and outputs and the potential environmental impacts of a product sys-

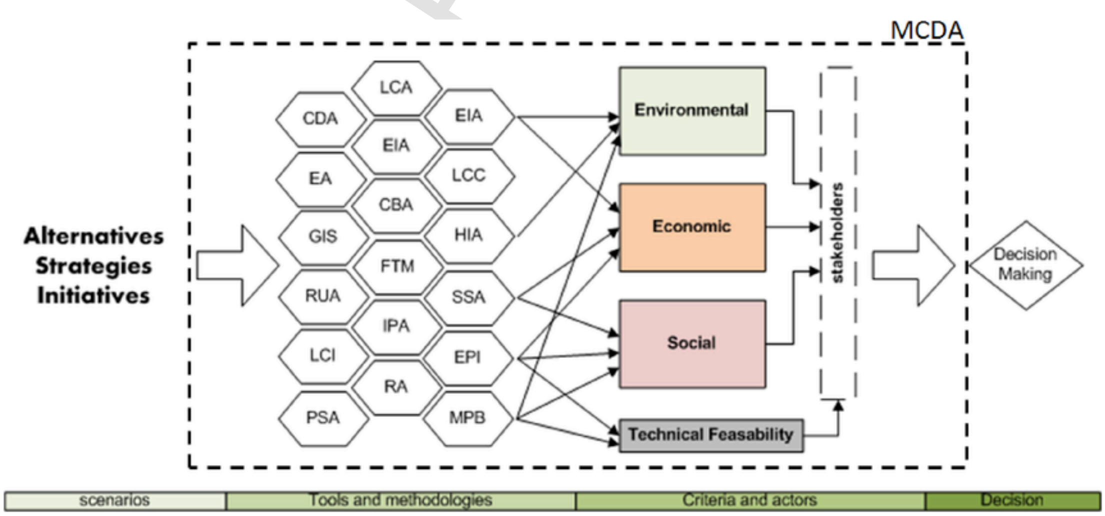

Fig. 1. General flowchart for sustainability decision-making.

tem throughout its life cycle (ISO, 2006a, 2006b). The latter is based on different protocols for eliciting inputs, structures, algorithms and processes to interpret and use formal results in actual advising or decision-making contexts (Huang et al., 2011). Thus, generally, the combination of MCA and LCA can occur in a two-ways path: LCA can be applied to add an environmental indicator to the MCDA process and MCDA can be used to interpret LCA outcomes. This relation is sometimes so near that some authors such as Benoit and Rousseaux (2003) also considered LCA as a specific method among the MCDA methods. There are many reasons for combining these tools, but according to Hermann et al. (2007), the main one lies in their complementary characteristics. LCA is objective, reproducible and standardized, whereas MCDA evaluation methods take into account subjective elements (such as the opinions of stakeholders and decision-makers) in the evaluation of the different criteria. On the other hand, the authors indicate that these combinations also have weaknesses. Operationally, they imply a large amount of information that needs to be collected and analyzed, which may block their implementation. Additionally, by including MCDA in this combination means that value-laden choices are made, influencing the results and introducing uncertainty through the loss of information when aggregating data (Hermann et al., 2007).

2.1. The need of LCA in MCDA

There are several types of MCDA techniques (Linkov and Seager, 2011; Shields et al., 2011), each involving its own framework. They can vary from simple approaches requiring very little information to sophisticated methods based on mathematical programming techniques that require extensive information on each attribute and the preferences of the decision-makers (Greening and Bernow, 2004). What all multi-criteria methods have in common, according to Durbach and Stewart (2012), is the view that most decisions and decision-making can be improved by decomposing the overall evaluation of alternatives into evaluations on a number of usually conflicting criteria relevant to the problem, in a systematic way (Ekener et al., 2016). MCDA can be used to identify a single most preferred option, rank scenarios, grouping or simply distinguish acceptable from unacceptable possibilities (Belton and Stewart, 2002). However and as already stated, when it comes to sustainability, the MCDA approach individually is unable to identify efficient levels of pollution production or resource use (Zagonari, 2016). Myllyviita et al. (2016) confirms this situation in “solely using MCDA to support sustainability assessments is not suggested, since MCDA, in many cases, needs input from other tools and methods, such as LCA”. Therefore, the use of LCA to assess scenarios in order to feed MCDA methods with environmental content have become perhaps the most usual combination between both methodologies (for instance, see Bogacka, 2015; Burchart-Korol et al., 2014; Von Doderer and Kleynhans, 2014).

2.2. The need of MCDA in LCA

Tsang et al. (2014) explains that, even though LCA is a broad-scope environmental management tool, it leaves decision-makers with the challenge of appropriately integrating this information into their decisions. This is primarily due to the fact that LCA has been developed without an explicit link to a specific decision analysis framework (Ramanujan et al., 2014). Essentially, LCA results in a list of environmental impacts (or damages) that may be understood as performance indicators of the product system under analyses. However, decisions and conclusions based on those outcomes are still dependent on a vital step after the inventory being characterized into those indicators, the interpretation. Unfortunately, this task is not always straightforward, especially in case of comparison between different alternative scenarios fulfilling the same function (Benetto et al., 2008). According to Le Tenó (1999), difficulty lies in the quantity of data, the multiple unit types, the various media to which substances outflow, judgmental values to be applied and the uncertainty of background and foreground data. This situation is aggravated when LCA outcomes show trade-offs between different scenarios. For instance, the mid-point category scores may not point to a single definitive choice as the ‘best’, i.e., the least environmentally damaging system. One alternative may be better with respect to global warming potential, while another is better with respect to ecotoxicity (Shields et al., 2011). Additionally, Laurin et al. (2016) states that the current visualization techniques used in LCA, as bar graphs of characterization results, can be misleading and do nothing to aid in assessing potential trade-offs. In effect, these results may be difficult to interpret by stakeholders and decision-makers.

Therefore, a remaining methodological challenge for environmental managers is how to construct a comprehensive judgment of environmental performance from the many indicators assessed in LCA (Bengtsson, 2000; Curran, 2008; Hertwich and Hammitt, 2001). This challenge can be approached using MCDA methods (Benoit and Rousseaux, 2003). Several authors noted that MCDA methodology can be applied to aid LCA with positive results (Cinelli et al., 2014; Geldermann and Rentz, 2005; Hermann et al., 2007; Jeswani et al., 2010; Miettinen and Hämäläinen, 1997; Seppälä et al., 2002; Soares et al., 2006) especially for preference measurement (Myllyviita et al., 2012). Laurin et al. (2016) explains that MCDA can enrich LCA outcomes by providing studied methods to assess trade-offs mainly because it allows a broader view of different aspects (Manzardo et al., 2014). Accordingly, Kucukvar et al. (2014) explains that this integration can provide a guidance for decision-makers, which can contribute to the development of sustainable strategies significantly.

Conceptually, MCDA is introduced in the LCA framework and standards as the ‘weighting’ step. This kind of combined application basically relies on using MCDA concept to aid in LCA trade-off interpretation. In this combination, the MCDA evaluation method is generally used to weight and sum LCA results into a single index (after classification, characterization and optionally normalization) (Agarski et al., 2016; Hermann et al., 2007). Fig. 2 shows the complex framework behind the environmental assessment in LCA and the multiple indicators that provide information for decision-making. Therefore, to aggregate the results at the midpoint or even the endpoint level into a single index/information (e.g. Product 01 > Product 02, Fig. 2) is desirable to make this an easier process. Coupling MCDA with LCA increases the usability of LCA in assessing product sustainability (Scott et al., 2016), is robust and, at the same time, easy to implement (Recchia et al., 2011). Reflex of this beneficial association is present in recent LCA studies as in Boufateh et al. (2011), Kumar et al. (2016) and Scott et al. (2016).

However, despite those experiences, the possibilities of MCDA methods are still poorly elaborated in the field of LCA (De Luca et al., 2015; Domingues et al., 2015; Seppälä et al., 2002). Since incorporating MCDA into LCA includes several sources of uncertainties and methodological disagreements, more research in this field is needed (Myllyviita et al., 2012). Consequently, some authors indicate that MCDA application that analyses objects in terms of the LCA is not common (as Motuziene et al., 2016). As there is a wide variation in terms of simple MCDA/LCA application, different approaches, criteria assessed, results and new MCDA methods for decision-making, one way to contribute to this field is to trace the actual framework on how MCDA is being used regarding LCA specifically.

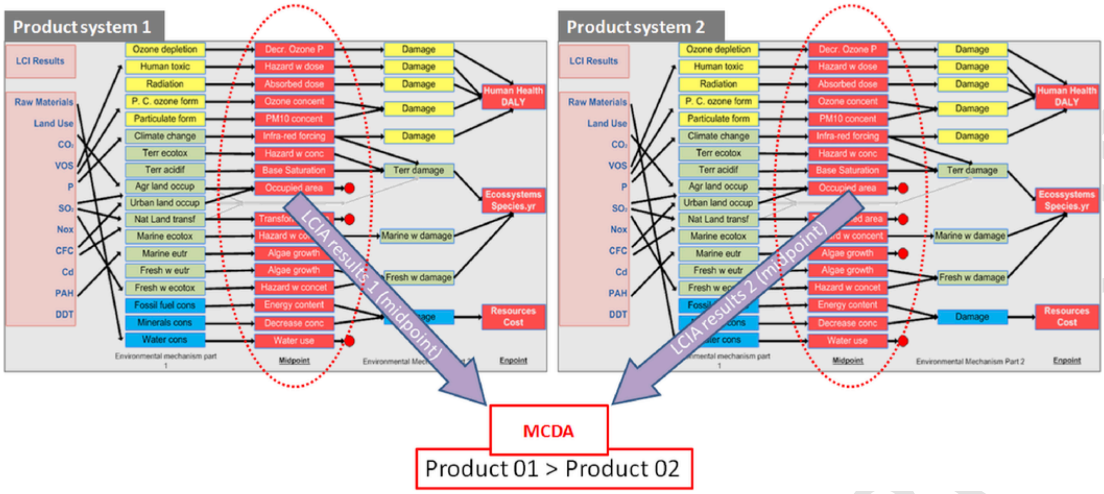

Fig. 2. LCA cause-effect chain and a schematic framework of a LCA comparison using MCDA for decision-making (based on Goedkoop et al., 2009).

Overviews regarding MCDA and Environmental Management are not novelties and have already been the theme of several papers in scientific journals. For instance, Herva and Roca (2013) reviewed combined environmental evaluation approaches (including LCA) and multi-criteria analysis for specific industrial sectors such as energy and wastewater treatment, whereas Benoit and Rousseaux (2003) and Geldermann and Rentz (2005) have worked the relations between MCA and LCA methodology phases. However, to date, none have been directed to the way MCDA is applied in a LCA context. Therefore, how this mutual application is being held is assessed in this article, more specifically to aid results interpretation. For that, the aim is twofold: (1) To investigate the current framework of this integration categorizing the field under aspects such as research type, applied MCDA method, considered criteria, influence and motivations for MCDA application in LCA; and (2) To map references in this field regarding the position in LCA steps and level of decision-making in terms of criteria. The expectation is that this paper will indicate some important fields for further research and facilitate the path of those seeking to decrease uncertainty in life cycle thinking, supporting the research community concerned with improving the decision-making procedure.

3. Materials and methods

The papers were gathered from SCOPUS and Web of Science (WoS) databases through a specific set of key-words. According to Zanghelini et al. (2016) both have high incidence of access in academic and scientific fields. Consequently, several reviews and bibliometric studies, especially for LCA or MCDA also considered those databases (Hou et al., 2015; Myllyviita et al., 2016; Qian, 2014; Souza and Barbastefano, 2011; Subramanian et al., 2015; Xu and Boeing, 2013; Zanghelini et al., 2016).

The keywords applied to the databases were: “life cycle assessment” or “life cycle analysis” or “LCA” and “multi-criteria decision analysis” or “multi-criteria analysis” or “MCDA” or “MCA” in all possible combinations among them. In SCOPUS, those key-words were inserted in the search fields of (article title), (abstract) and (keyword), published in all years until 2016, for all types of documents. For Web of Science, they were settled as (title), (abstract) and (keywords) search fields, for all years until 2016 and journals as a publishing vehicle. These sets of keywords were chosen to look for comprehensive publications regarding LCA and MCDA as well as enable one to have a proper yet manageable set of papers. The findings were refined through a previous content review of title and abstract whereas repeated publications were discarded. Since the scope of analysis is the MCDA and LCA integration, only documents that applied (in any matter) MCDA and LCA were considered. In this case, for instance, papers that applied only MCDA and considered LCA for discussion purposes were not considered (and vice versa). The selected papers that complied with these research boundaries were analyzed in detail to extract the information required by a comparative table. Table A1 was developed based on several aspects of the final group of published works, including direct information, such as reference, date of publication, authors, MCDA method, LCA method and others that were not always clear, for instance, position of MCDA in LCA steps, motivations, criteria applied to perform decision-making, and so forth. The outputs from Table A1 were divided into two main analyses: (1.) General analyses of this particular field of research, and (2.) Content analyses. For the former, a performance analysis on the basis of bibliometric analysis was conducted (Hou et al., 2015) which aims to evaluate the characteristics of the publications such as journals, evolution through time, dominant publishing type, main publishing vehicles and main economic sector (e.g. livestock, waste management.). The second represents a more in-depth interpretation, seeking for patterns and trends in how LCA and MCDA are being applied and what kind of results and conclusions were made by the researchers.

4. Results and discussion

The survey without any filter identified 427 documents from SOPUS and 265 references from WoS. After refining this group with the proposed outlining strategy, 109 papers were accessed (listed in Table A1 in the Supplementary material).

4.1. General analysis

By assessing this group of papers over time, it is possible to note that the first paper dates from 1995. Bloemhof-Ruwaard et al. (1995) published a paper titled “Environmental Impacts of Fat Blends: A Methodological Study Combining Life Cycle Analysis, Multiple Criteria Decision Making and Linear Programming”, where LCA was used to obtain an environmental measure for refined oils, to rank scenarios and identify the best choice among different blends of fats and oils for the fuel sector. After 1995, until the early 2000s, the subject of MCDA and LCA was present but in a limited way. Only during the last 10 years it is possible to visualize an increasing behavior, with a more escalated period from 2010 to date (Fig. 3). Making a parallel with what happened in terms of LCA maturity in the same period of time, during the 90s, LCA standards (ISO, 1997, 1998; 2000a and 2000b) and initial guidelines were published (for instance, SETAC, 1993). These were key factors for the initial use and publication of the LCA by industry and governments, since, due to the standards, the tool recovered its reliability and robustness. However, only with major developments in terms of LCA methodology, growth of databases, software availability and other fields of application of LCA results (e.g. labeling) is that interest in LCA increased and its application was spread to many other economic sectors. This behavior reflects in the increasing number of papers that are noted in Fig. 3 in the last decade integrating LCA with MCDA. Several other authors, delimiting different kinds of LCA publishing groups, have shown this same tendency as Chen et al. (2014), Hou et al. (2015), Qian (2014), Xu and Boeing (2013) and Zanghelini et al. (2016).

Table 1 presents some general information summarized from Table A1. Regarding scientific journals, the main vehicle is the Journal of Cleaner Production, with 12 papers followed by the International Journal of Life Cycle Assessment with 7 publications. These journals are dedicated to sustainability promotion and LCA, respectively and not surprisingly, the main vehicles in this matter. Nevertheless, what draws attention in this analysis is the wide variation of different journals, where 76 different vehicles complete the list from the most diverse fields (e.g. energy, waste management, building, fuels, among others). Classifying papers into types of research, 43 papers were labeled as “Application”, i.e. when authors simply applied some existing MCDA/LCA methodology to assess its own scenarios. Examples of this kind of paper are Atilgan and Azapagic (2016) and Myllyviita et al. (2012). Both papers applied LCA to insert environmental indicators in decision-making. The former used the Multi-Attribute Value Theory (MAVT) with LCA to evaluate different scenarios for electricity production in Turkey using the CML2001 method as the input/feed for the environmental criteria along with social and economic criteria. Similarly, Myllyviita et al. (2012) used the characterized results from ReCiPe method (at midpoint level) for pulp and paper production scenarios to assess the different impact categories with Simple Multi-Attribute Rating Technique (SMART) to find the best scenario. The dominance of “Application” papers was an expected condition since the ultimate (and most usual) interest of stakeholders is the final decision, which is sustained by results from simple application. Besides, such tools have a multidisciplinary condition, enabling its use to any subject, which may also explain the wide variation in journals. Accordingly, Herva and Roca (2013) affirmed that among the topics covered in their review, applications were found for all the MCDA methods previously discussed by the literature (except one done for MACBETH at that time).

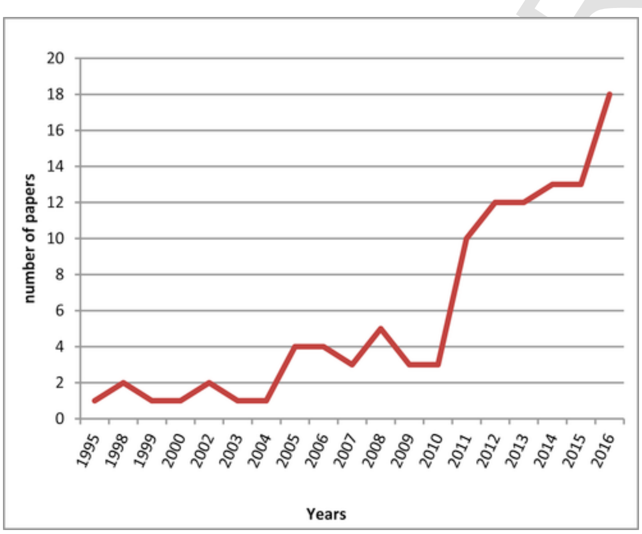

Fig. 3. Evolution over time of published papers in this survey.

Table 1
General information.

Publishing Vehicle	**N**
Journal	93
Conference	14
Report	2
Journal	**N**
Journal of Cleaner Production	12
International Journal of LCA	7
Clean Technologies Environmental Policy	4
Sustainability	4
Risk Analysis	3
Environmental Science and Technology	3
Energy Policy	3
Waste Management	3
Others	70
General Subject	**N**
Application	43
Review	22
Creation and case study	21
Proposition and case study	11
Review and case study	4
Creation	4
General proposition	4

In the sample, 22 other references were categorized as “Review”. These papers generally aggregate broader information into a specific subject. French and Geldermann (2005) for example, discussed which tools and techniques may be more appropriate for stakeholder involvement and how they might be deployed within the wider decision-making process. Others brought specific state of the art analysis, such as Strantzali and Aravossis (2016) for renewable energy or Subramanian et al. (2015) for the nanotechnology sector. It is also possible to find a few papers conditioned as “Review and case study”, where the subject is reviewed and still applied to some example for illustrative demonstration. This significant release of review works in the group of papers (24%) may indicate that the field of decision-making and life cycle thinking is still being developed in terms of methodology, a condition that reflects the necessity of discussion and compilation publishing. This effect is illustrated by motivations that led authors to this kind of publication (see Table A1), often based on a lack of information and literature in the field (French and Geldermann, 2005; Myllyviita et al., 2016; Seppälä et al., 2002) or because new tools, methods and trends were created (Liu et al., 2011; Mootanah, 2005; O'Riordan and Phear, 2012).

In sequence, 21 and 11 references were classified as “Creation and case study” and “Proposition and case study”, respectively. The first group includes studies that proposed new methodologies/approaches, whereas the second group integrated different (but already existing) methods or different insights for existing approaches. To some extent, both group of papers applied its propositions to a real situation as in a case study. Two representative papers of this group in the survey are Le Tenó and Mareschal (1998) and Motuziene et al. (2016). Le Tenó and Mareschal proposed a new approach (PROMETHEE I) able to handle interval performances based on PROMETHEE. In a different way, Motuziene et al. created a general algorithm mixing different approaches including LCA (IMPACT method), LCC, COPRAS and AHP for the envelope selection of the energy efficient single family house. Completing Table 1, papers were also classified as "Creation", when a methodology is created but not applied; and "General proposition", when authors discuss methodology (beyond a review) to guide practitioners. The creation of methods and proposition of approaches is a condition aligned with the previous statement that the LCA/MCDA field is a growing research subject as well as the unsolved problems in sustainable decision-making.

4.2. MCDA in LCA

By tracing a relation between MCDA and LCA, it is possible to identify two spots where MCDA is frequently used to aid LCA interpretation: at the LCI level and the LCIA/LCA Score level. In addition, although uncommon, MCDA has already been used for methodological alternatives, such as the definition of impact categories, and also in a parallel way for the LCA steps: when MCDA is used to create weight to impact categories. This last case is classified as LCIA development within LCA methodology. This condition illustrates a statement from Seppälä (2003), who indicated that MCDA within an LCA study can be used in all LCA phases. Fig. 4 presents a schematic framework of this relation regarding its main applications and the kind of influence that generates into decision-making.

In the mapping research from Fig. 5, the criteria (environmental, economic, social and technical) assessed was related in each study that effectively applied or proposed an integration of LCA and MCDA regarding the position of MCDA in LCA (phases). For example, references positioned in "Methodological Choices" applied MCDA to aid impact categories selection or to identify significant aspects in LCI. Publications located in LCI on the '*LCA Localization*' axis assessed indicators at the inventory level, such as consumptions (water, energy) and generations (waste, CO_2). Meanwhile, references positioned in LCIA assessed outcomes from LCIA methods such as midpoint impact categories (Global warming, Eutrophication and Acidification) and endpoint damage categories (Human Health, Ecosystem and Resources). Finally, references positioned in the LCIA development "umbrella" are those that extract significance of impact categories and create a set of weights for the weighting step in LCA. These possibilities are addressed in detail in the next sections.

4.2.1. MCDA in LCA methodological decisions

For the purpose of a better understanding, methodological decisions were positioned in the Goal and Scope Definition phase, although it can be argued that a LCA practitioner made decisions in all phases of a LCA. Therefore, in this phase, the intent is to set MCDA when it is applied to support a major methodological decision. Even though it is the first phase in the LCA framework (ISO, 2006a), this integration is uncommon as demonstrated in Fig. 5. Only Myllyviita et al. (2012) is classified in this column as a panel-based MCDA that was used to add environmental impacts, not previously considered as being included in LCA. According to the authors, results show that the panelists recognized deficiencies in the impact categories of the ReCiPe methodology. Papers located in the middle of two columns, such as Liu et al. (2012), considered elements of two different locations in LCA phases. In the work of Liu et al., LCA was used to identify the cause-effect chain (aspects of the life cycle) and then apply MCDA combined with Risk Analysis to aid decision-making on waste management plants. The identification of the cause-effect chain is somehow a path that a LCA practitioner has to perform when outlining scope definitions (as product system boundaries) and beginning to gather data where aspects must be identified. That is the reason Liu et al. (2012) is positioned between Methodological Choices and LCI on Fig. 5.

Myllyviita et al. (2012) explains that in situations where relevant impact categories may not be obvious, selecting impact categories with the assistance of MCDA in a process would deepen the standard LCA. This rationale can be expanded to other methodological options. For instance, MCDA could also be used to define the allocation approach, considered one of the most controversial definitions in LCA (Rebitzer et al., 2004; Zamagni et al., 2009) or even to aid in the definition of Inventory Methods (often not even considered by LCA practitioners when performing a LCA). This kind of application can already be found in scientific literature. In a recent Master thesis published by Souza Junior (2015), MCDA was applied to a group of specialists to indicate a better allocation approach in an open-loop LCA case. According to the author, "for the process of choosing the

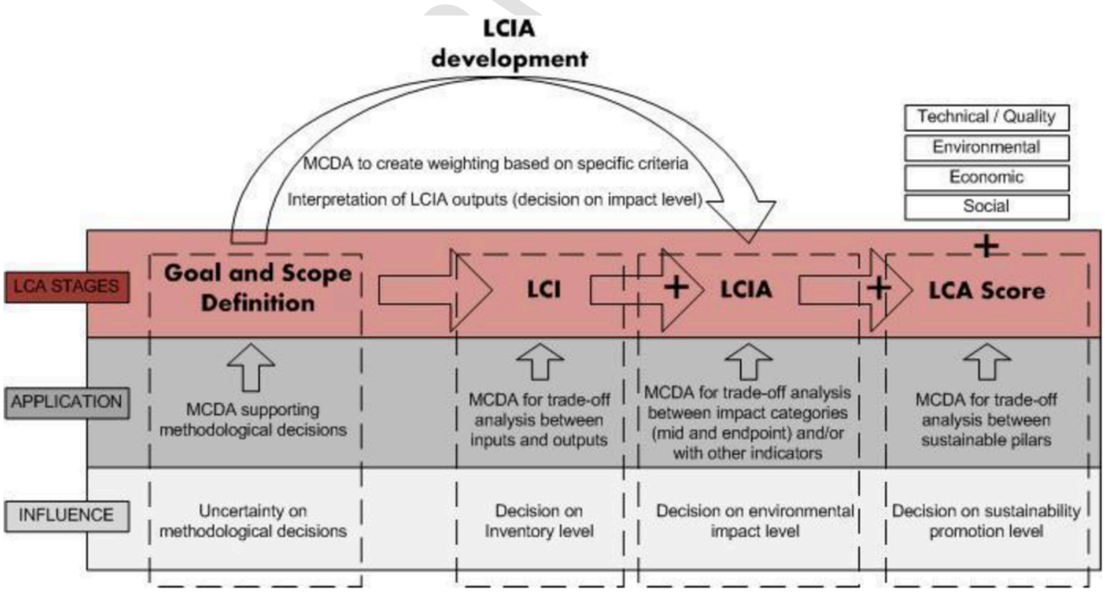

Fig. 4. Levels where MCDA may be integrated to aid interpretation on LCA approach.

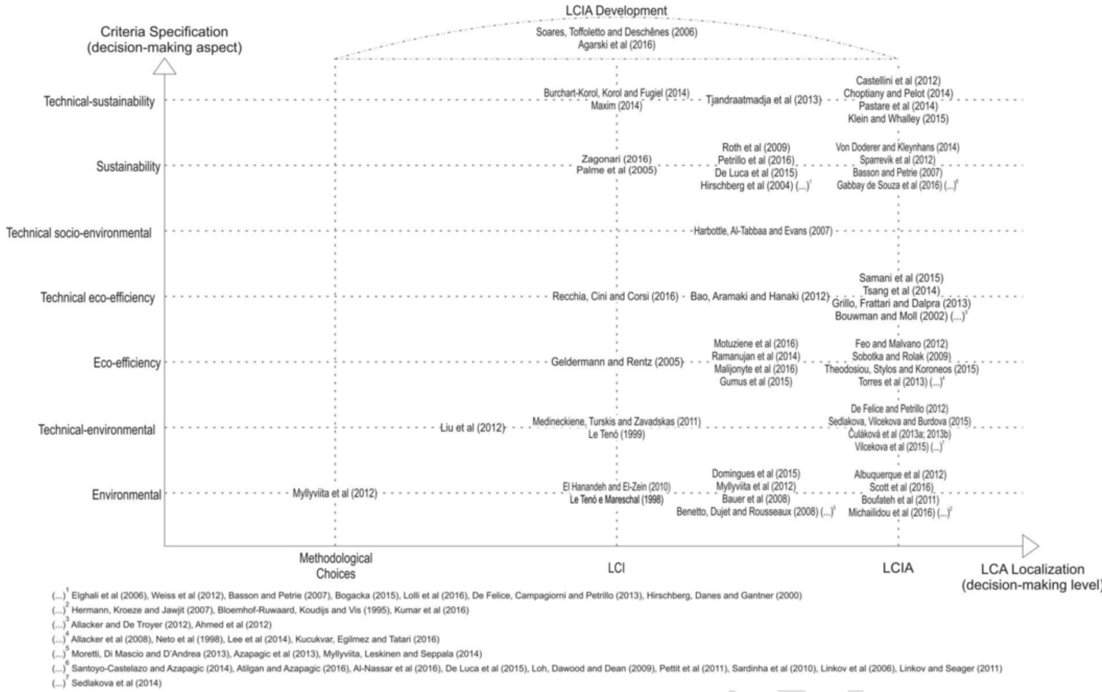

Fig. 5. Mapping of references in the LCA approach and decision-making aspect.

allocation method, the proposal to use a multi-criteria analysis method for decision-making has shown good efficiency". In this sense, MCDA at the Goal and Scope Definition may influence an uncertainty reduction in decision-making related to the LCA methodological options.

4.2.2. MCDA in LCI decision

At the LCI level, decisions are made at the level of flows in a life cycle of a product system (Fig. 4). The influence of such positions of MCDA application in LCA phases is a decision on the inventory level, where reduction of flows (either inputs or outputs) indicates the best option. El Hanandeh and El-Zein (2010), for instance, applied MCDA where indicators were only environmental aspects (including acidification gases, smog precursors, heavy metals, dioxins, greenhouse gas (GHG) reduction, green energy recovery and landfilled waste) to select a management strategy for the bio-degradable fraction in the municipal solid waste of Sydney (AUS). Some authors also considered other facets of sustainability at this level of LCA decision-making (e.g. environmental and economic aspects as in Geldermann and Rentz, 2005; environmental, social and economic as in Zagonari, 2016; Palme et al., 2005) or considered LCI altogether with LCIA indicators in the decision-making process (e.g. Bao et al., 2012; De Felice et al., 2013) as represented by Fig. 5. This situation can be found in Bauer et al. (2008), whose research included midpoint impact categories from Ecoindicator 99 and flows as radioactive and non-radioactive waste as criteria in the MCDA approach for the decision-making procedure to rank energy sources in Switzerland.

The main motivation of MCDA applied to the LCI level is to find the best option in terms of sustainability of different scenarios/options (De Felice et al., 2013; Medineckiene et al., 2011; Palme et al., 2005; Zagonari, 2016). However, even though reduction in LCI aspects frequently represents less environmental impacts, this cannot be considered a rule of thumb (as trade-offs between impacts categories may occur after characterization). Perhaps due to this fact, there are fewer papers located in this phase if compared to LCIA (Fig. 5), also inventories generally have a higher number of flows, increasing the likelihood of having trade-offs among the set of criteria. Others also indicate the necessity of trade-off consideration among different environmental aspects in the decision (Bao et al., 2012), a very common motivation of MCDA sustainability studies. The most present trade-off, when analyzing all 35 papers linked to the LCI step, is the environmental/economic/social dimensions (13 references), which demonstrate the interest of decision-makers in considered sustainability at this level of LCA. Incidentally, from the total references that considered any of the indicators at the LCI level (35), there are more papers (25) using MCDA considering both LCI and LCIA as inputs to perform decisions when compared to those that only considered information from the LCI phase (10 publications). In the case of the 10 papers that exclusively considered the LCI indicator, economic dimension is present in 8 from which 3 calculated the environmental/economical social facet in the decision-making process.

The most common criteria at the LCI level is Waste Generation, in several forms as radioactive, hazardous, landfilled, non-recyclable (present in 15 papers) followed by Energy consumption (12 appearances) and Water consumption (found in 10 occasions). These aspects are present in almost any product system and have an important effect in costs for the manufacturers, whether it is expensive (or highly consumed) as energy, or because it is costly to treat (in the case of final disposal of waste). Therefore, it is not by case that those elements are present in decision-making at the LCI level. Other indicators that have shown an important presence is atmospheric emissions per substance (e.g. CO, CO_2, N_2O, PM, etc.), elements that are linked to control technologies, and in this case also gather importance by environmental regulation laws. This situation may also explain the strong presence of economical dimensions at this level of decision-making.

Regarding MCDA tools, authors have shown preference for outranking approaches with 9 papers applying methods from this family (PROMETHEE, ELECTRE and variations). Weighting Sum Approach (WSA) and Analytical Hierarchy Process have appeared 6 times each, whereas Utility-based approaches have appeared only on 4 occasions. This is a trend in MCDA studies, even more related to environmental (sustainability) decisions because outranking methods have a (partial) non-compensatory approach. WSA and AHP are considered friendly approaches (for users and decision-makers) having good presence in this survey, even though it presents compensatory behavior.

4.2.3. MCDA in LCIA decision

In the LCIA phase, MCDA is used to aid the interpretation of impact categories trade-offs - at midpoint and endpoint levels as exemplified in Fig. 4. This is due to the complex nature of the impacts generated by different product systems (or alternatives), situations that have already been highlighted by Boufateh et al. (2011), “it is not obvious to distinguish the best alternative because the differences between criteria values of alternatives cannot be easily compared in regards to the impact categories, their units and their degree of seriousness”. Several authors have used MCDA to solely asses the trade-offs between LCA indicators at the midpoint level (Benetto et al., 2008; Hermann et al., 2007; Kumar et al., 2016; Sedlakova et al., 2014; Vilčeková et al., 2015) and at the endpoint level (Michailidou et al., 2016). Besides those aforementioned papers, in this phase, the main rationale to integrate MCDA with LCA is to deal with LCIA outcomes in parallel with economic, social and technical aspects. This is by far the most frequent use of MCDA in LCA with 43 publications (40% of our sample). For example, Petrillo et al. (2016) recently published a paper analyzing the outcomes of Ecoindicator 99 method at the endpoint level, with economic aspects (operational cost, disposal, etc.) and social indicators (health and safety, people development …) by the AHP method, to rank power generation systems. The reason behind this integration is to “support decision-makers in complex decision problems in the field of environmental sustainability” (Petrillo et al., 2016).

The motivation for applying MCDA at this level is frequently the necessity of interpreting trade-off results and complex and uncertain information (Ahmed et al., 2012; Albuquerque et al., 2013; Atilgan and Azapagic, 2016; Boufateh et al., 2011; Choptiany and Pelot, 2014; Lee et al., 2014; Loh et al., 2009; Scott et al., 2016; Von Doderer and Kleynhans, 2014), communication enhancement of results (e.g. single score), multi stakeholders involvement (Atilgan and Azapagic, 2016; Basson and Petrie, 2007; Choptiany and Pelot, 2014; Linkov et al., 2006; Loh et al., 2009), a TBL consideration of aspects (Lee et al., 2014; Santoyo-Castelazo and Azapagic, 2014; Sparrevik et al., 2012) and find the best choice of possibilities (Atilgan and Azapagic, 2016; Pastare et al., 2014; Samani et al., 2015; Sobotka and Rolak, 2009; Torres et al., 2013). A greater number of applications of MCDA methods in the LCIA phase is somewhat expected since this is a more preferable situation than decision-making based on LCI information (i.e. environmental aspects) alone and the reason is that LCIA results expressed in potential impacts seems to better communicate with stakeholders besides giving an environmental relevance to flows. This information is calculated though characterization models (present in LCIA methods) and encompasses relations between aspects that are not always visible when a decision is made on a LCI basis, even with the aid of MCDA methods. The most present LCIA methods in our survey are ecoindicator 99, 14 times; CML 2001, 13 times and ReCiPe, 5 times.

Through analyzing the most common environmental indicators used by the authors classified in this LCA step, it is possible to note the dominance of Global Warming (present in 51 papers - 47% of the group of papers and 65% of application and case study papers), followed by Acidification and Eutrophication. The presence of these indicators is clearly the dominant pattern in the group of papers as presented in Fig. 6. This cloud shows all environmental criteria present in the papers gathered in our survey, wherein larger words are more representative (i.e. are more recurrently applied by practitioners). Those three indicators are midpoint impact categories, which are especially recurrent in LCA studies, and generally required in Labeling programs (e.g. LEED) and by product category rules (PCRs) in environmental product declarations (EPD – programs) and are considered more robust since its characterization models are well accepted by stakeholders and the scientific community. This behavior was already indicated by Wang et al. (2009) and Herva and Roca (2013). Those authors indicate CO_2 emissions, greenhouse gases or a global warming category as a key issue in a LCA/MCDA context, followed by acidifying emissions (SO_2 and NO_x). Other important presences in our survey are performed by common impact categories in LCA, including Land Use, Smog, Ozone Layer Depletion and Ecotoxicity (see Fig. 6). When it comes to endpoint categories, the most used is Human Health as pointed in Fig. 6. Although, Ecosystem quality and Resources are also noticeable in the survey since an ISO-compliance LCA study covers all three protection areas (ISO, 2006a; 2006b). Finally and noteworthy to mention in Fig. 6, criteria at inventory level are dominated by Energy Demand, Water Consumption and Waste,

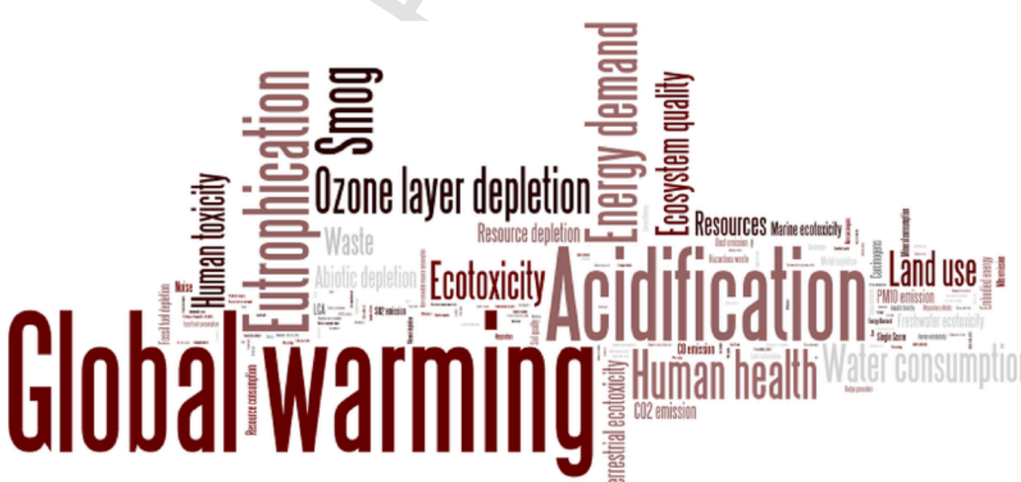

Fig. 6. Cloud of environmental criteria considered in MCDA and LCA studies.

three indicators subject of process efficiency control and also concern of manufacturers when it comes to environmental laws.

Besides environmental dimensions, others facets of TBL are being considered. Preferential economic criteria are related to direct costs of production/plant installation as in operational costs, raw material acquisition costs, investment costs, labor costs and generated values related to products, for instance, income or added value or gross capital. When the social dimension was considered in case studies, common criteria was generally job creation, labor safety and general acceptance of the industry (or product) of the impacted area/society. Life Cycle Costing (LCC) as a matter of methodology to raise economic criteria was also found, but only in Grillo et al. (2013), Loh et al. (2009) and Motuziene et al. (2016). Regarding the social dimension, Social LCA (SLCA) was found only in general propositions as in Loh et al. (2009) and Pettit et al. (2011).

When MCDA is applied at the LCIA level there is a clear preference of practitioners for WSA and AHP approaches with 16 and 15 appearances, respectively. Many authors have chosen those methods based on its simplicity (Von Doderer and Kleynhans, 2014) and straightforward nature (Bao et al., 2012). Similarly when MCDA is applied at the LCI level, at the LCIA level, outranking methods have shown a recent and important presence with 11 papers, somehow confirming a trend to opt for this family of MCDA methods.

4.2.4. MCDA in LCIA development

Only two papers were identified in a parallel LCA phase, Soares et al. (2006) and Agarski et al. (2016), both dealing with the application of MCDA to define weights for impact categories, used afterward in the weighting step. This kind of relation, even though positioned without a specific LCA stage, seeks to improve the interpretation in the LCIA phase, when a practitioner applies normalization, weighting and aggregation of LCIA results into a single score. Although controversial amongst LCA practitioners, it is an important aid in the interpretation of trade-offs in LCIA outcomes, but in a broader way, since a set of weights can be applied to any product system. In weighting, there are different methods behind the definition of a set of weights, such as distance-to-target or monetization. However, if the essence of decisions on such a broad subject is to consider all stakeholders in this process, there are surprisingly few papers on this topic. Soares et al. (2006) and Agarski et al. (2016) encompassed environmental and technical aspects in their MCDA approach (Fig. 5). The first applied a panel-based AHP to elicit implications for human health, ecosystem health and natural resources (three damage categories – environmental dimension), scale, duration, reversibility, distance-to-target and uncertainty (technical sphere from impact behavior). The second, assessed ReCiPe endpoint (H) outcomes (i.e. climate change, metal depletion, etc.) as well as time, area, irreversibility and uncertainty from a technical prism through AHP and fuzzy logic approaches. Therefore, both studies have a similar MCDA basis since the used criteria are identical, duration/time, reversibility/irreversibility, scale/area, uncertainty; Impact categories are equivalent, and; AHP was the MCDA approach.

4.2.5. Criteria preferences

Environmental and environmental related MCDA (the green circle in Fig. 7) represent the vast preference of studies integrating MCDA with LCA, whereas economical (blue circle) and social (yellow circle) prisms have good appearances, but are always together with environmental criteria. Environmental criteria alone was the preference of 16 papers, whereas 13 references opted for economic and environ-

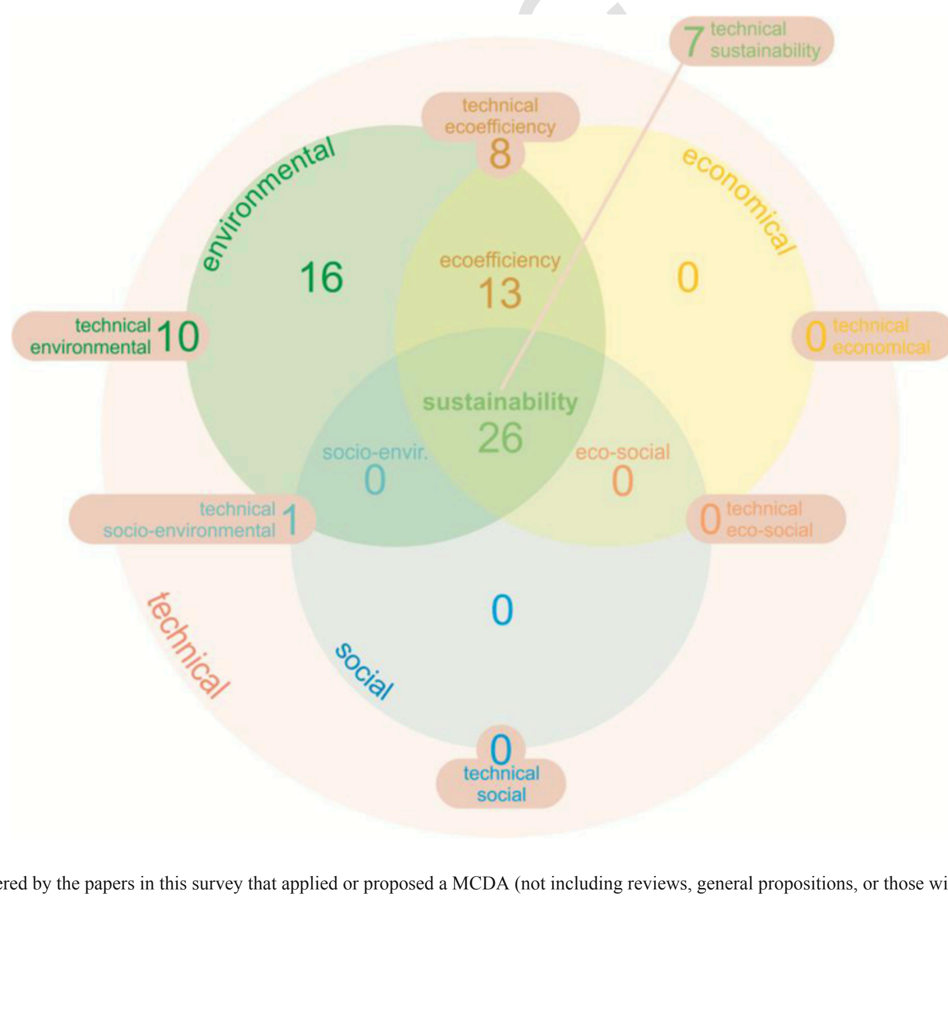

Fig. 7. Criteria covered by the papers in this survey that applied or proposed a MCDA (not including reviews, general propositions, or those without defined criteria).

mental pillars, decisions made at the eco-efficiency level (as in Feo and Malvano, 2012; Gumus et al., 2015; Sobotka and Rolak, 2009; and others when eco-efficiency line crosses LCIA column in Fig. 5). The social aspect is considered integrated with the environmental aspect, but only when technical indicators are accounted altogether (as in Harbottle et al., 2007). In fact, technical issues permeate all prisms raised in our survey (i.e. with environmental criteria, there is the technical-environment level; with economic and environmental criteria results in the technical eco-efficiency dimension; with social and environmental criteria reaches the technical socio-environment dimension; and even with TBL criteria, technical sustainability). This indicates the significance of such criteria for decision-makers, generally linked to product functionality/performance (e.g. efficiency of electricity plants as in Maxim, 2014 or durability of wood lumber floors as in Tsang et al., 2014) or security (e.g. heat transmittance and thermal storage as in Čulákova et al., 2013). Finally, it is also possible to note in Fig. 7 that the most common multi-criteria condition is performed by the environmental, social and economic set of papers (26), a situation where decision-making is held at the Sustainability level (Basson and Petrie, 2007; Roth et al., 2009; Sparrevik et al., 2012; and others mapped in Fig. 5). These findings are partially aligned with the statement by Herva and Roca (2013) that "MCA methods were rarely applied to decision making that considered solely environmental criteria. Rather, they dealt with indicators from the different dimensions of sustainability". Others include technical elements, being the technical-environmental analysis as the most common, followed by technical sustainability and technical eco-efficiency.

The predominance of environmental (and environmental related) dimensions in the survey occur as only "environmental" as LCA has already been standardized. It is more robust and therefore, more widely accepted by the scientific and non–scientific communities. Because of this, environmental criteria did not show major variations (e.g. global warming was present in the major part of studies). The economic dimension is frequently considered due to costs or investments necessary to implement the alternatives or operate product systems (or scenarios) and the social dimension presented several criteria, headed by job creation (in several forms), followed by health and safety issues and acceptance of alternatives by communities. Different from the environmental dimension, criteria in social and economic spheres have shown a wide conceptual variation. In other words and for example, even though job creation was present in most of the papers, it was also defined in many different ways such as the number of permanent jobs created, direct employment creation potential, and number of formal e-waste workers. These results may indicate opportunities for further economic and social LCIA method (or impact categories) development, since these criteria represents stakeholders' interests, and these two approaches are not yet standardized and/or well agreed upon in the scientific community. Fewer papers applied Life Cycle Costing and Social Life Cycle Assessment as methods (to perform economic and social dimensions respectively) in the interface with LCA, which demonstrates that sustainability-LCA is still not a common consideration in MCDA studies.

5. Conclusions

In this paper, a review was performed of the published works in the field of MCDA integrated with LCA methodology in order to assess how MCDA techniques are being applied in the LCA context to support results interpretation. The aim was to investigate the current framework of this integration and map the field for the research community concerned with improving the decision-making procedure with an expectation to enhance clarity on the subject and facilitate the path of those seeking to reduce the decision-making uncertainty based on life cycle thinking approaches.

The time evolution of the published samples demonstrates a solid and constant increase in the number of papers published following the same pattern as in other fields regarding sustainability such as LCA itself. The evolution, as well as the kind of research that were identified in the survey, indicate a field that has a growing interest based mainly on the need to have better decisions in the sense of sustainability and the need to consider several dimensions in order to make the best possible decisions.

In this group of 109 references, the most recurrent application of MCDA in a LCA is at LCIA phase, where the main goal is to assess trade-offs between different impact categories (at midpoint and/or endpoint levels) or between environmental and other dimensions (economic, social and technical criteria are considered). At this level, the most recurrent MCDA approach is WSA and AHP. However, the recent increase of the outranking family method application is a trend, mainly due to its non/partial compensatory behavior. The major part of the papers in our survey considered TBL dimensions or just the environmental aspect in this LCA step. Less common, but well represented, MCDA has shown that decisions are made in terms of aspect consumption and generation reduction at the inventory level (LCI step), where energy and water demands altogether with waste generation were the main interests in terms of criteria for the decision-making process. At this time, outranking methods are more common, although WSA and AHP maintained an important presence. Only one paper was classified in the Goal and Scope definition phase (first step of LCA standardized methodology) and applied to MCDA to define impact categories that represented the stakeholders' preferences. Despite this unusual application of MCDA in LCA, other controversial methodological options may be supported by decision aid approaches, such as the allocation approach and the inventory method. In the end, there is still a lack of studies directed to MCDA in the Goal and Scope definition, and how such integration could possibly influence or benefit an uncertainty reduction related to the LCA methodology. There is one last interface of MCDA in LCA, and it is somehow parallel to a traditional LCA, associated with LCIA development. This is the case when authors used MCDA to elicit impact category significances (or weights) to perform weighting in LCIA/interpretation of LCA results. Two papers were identified in this section. The low number of papers on this subject reflects the fact that weighting is an optional phase in a LCA study and is considered by many authors as a controversial step due to its subjectivity. However, it can be argued that interpreting LCA results without any significance related to the impact categories assigns the same importance to each impact (which may be a worse situation). Thus, there is still a need for a more in-depth research on this theme, where MCDA may play a significant role.

The wide variation in terms of choices, presuppositions and diverse outcomes in a LCA indicates that interpretation of results is still very complex and there is not a preferable methodological path to solve the final decision issue, even more when different players must participate. That is the reason auxiliary methods are needed, such as MCDA. Furthermore, besides LCA interpretation, there is a clear and increasing interest in decision-making at the TBL (sustainability) level. In this case, there is a clear necessity for the development of new methods or improvement of existing approaches, such as LCC and SLCA. One possible way to contribute to this task is to analyze economic and social criteria that already have been considered in studies like those identified in this paper.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jclepro.2017.10.230.

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List of abbreviations

ANP : Analytic Network Process
AHP : Analytic Hierarchy Process
AUS : Australia
CBA : Cost-Benefit Analysis
CDA : Critical Discourse Analysis
CF : Carbon Footprint
CPP : Composition of Probabilistic Preferences
COPRAS : Complex Proportional Assessment
DfE : Design for Environment
DtT : Distance to Target
EA : Environmental Analysis
ED : Energy Demand
EIA : Environmental Impact Assessment
ELECTRE : ELimination Et Choix Traduisant la REalité
EPD : Environmental Product Declaration
EPI : Environmental Performance Index
FTM : Freight Transport Management
GIS : Geographic Information System
GHG : Greenhouse Gas
GWP : Global Warming Potential
HIA : Health Impact Assessment
IPA : Importance Performance Analysis
ISO : International Organization for Standardization
LCA : Life Cycle Assessment
LCC : Life Cycle Costing
LCI : Life Cycle Inventory
LCIA : Life Cycle Impact Assessment
LCT : Life Cycle Thinking
LEED : Leadership in Energy and Environmental Design
MACBETH : Measuring Attractiveness by a Categorical Based Evaluation Technique
MAUT : Multi-attribute Utility Theory
MAVT : Multi-attribute Value Theory
MCDA : Multi-criteria Decision Analysis
MSW : Municipal Solid Waste
MPB : Multi-period Budgeting
N/A : Not Applicable
NAIADE : Novel Approach to Imprecise Assessment and Decision Environments
PCR : Product Category Rule
PM : Particulate Matter
PSA : Probabilistic Safety Analysis
PROMETHEE : Preference Ranking Organization Method for Enrichment Evaluation
RA : Risk Analysis
RUA : Routine Urine Analysis
SETAC : Society of Environmental Toxicology and Chemistry
SMART : Simple Multi-Attribute Rating Technique
SSA : Specific Surface Area
TBL : Triple Bottom Line
TOPSIS : Technique for Order Preference by Similarity to Ideal Solution
US : United States
WoS : Web of Science
WSA : Weighting Sum Approach