Life Cycle tools combined with multi-criteria and participatory methods for agricultural sustainability. Insights from a systematic and critical review.

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Abstract

Life Cycle (LC) methodologies have gained a great consensus in agricultural sustainability assessment, even if, in the same time, they have been not exempt from critics because of the frequent use of assumptions and the recourse to subjective choices. To cope with these weaknesses, Multi-Criteria Decision Analysis (MCDA) and/or participatory methods are highly suitable, as well as to balance and integrate different sustainability dimensions. The purpose of the study is to highlight how life cycle approaches were combined with MCDA and participatory methods to address agricultural sustainability in published scientific literature. A systematic and critical review was developed, highlighting the following features: which multicriterial and/or participatory methods have been associated to LC tools; how they have been integrated or complemented (methodological relationships); the intensity of involvement of stakeholders (degree of participation); which synergies have been reached by combining the methods. The review methodology consisted in the implementation of multiple iterative steps. The search of literature have been carried out with inclusion and exclusion criteria. Form a first population of 75 papers published from 1997 to 2016, 22 most recent papers assessing the sustainability of agricultural and forestry-based products were selected. The review revealed which assets and synergies are achievable by combining the methodologies. The main typology of integration was represented by multicriterial frameworks integrating LC evaluations. LC tools can provide MCDA studies punctual and global information on how to reduce negative impacts and avoid burden shifts; while MCDA methods can help LC practitioners to deal with subjective assumptions in an objective way, to take into consideration actors' values and to overcome trade-offs among the different dimensions of sustainability. These synergies are of utmost importance towards the development of new integrative assessment tools such as Life Cycle Sustainability Assessment (LCSA).

Keywords: Agricultural sustainability, Life Cycle Assessment (LCA), Life Cycle Costing (LCC), social LCA, Multi Criteria Decision Analysis (MCDA), participative techniques

1 Introduction

For a long time, agricultural research focused on practices to increase productivity of land, crops and farming inputs, whereas in the last decades the attention shifted to sustainability concerns, such as limiting the environmental damages and reducing the ecological footprint of agriculture (Struik et al., 2014). Due to its direct connection to the use of natural resources, agriculture, as well as forestry, has great responsibility in terms of threats for biodiversity and quality of the environment (Kleijn et al., 2009; Gabel et al., 2016). Food industry, being one of the largest industrial sector in the world, is responsible for greenhouse gas emissions due to the high consumption of energy that impact in terms of global warming (Roy et al., 2009). At the same time, consumers became more conscious and sensible, and increased the demand for new qualities: safe, ethical and environmental friendly food (Boer, 2002; Roy et al., 2009).

Sustainability is a conflicting concept itself, and a univocal definition does not exist. Many authors agree on defining sustainability science as a multidisciplinary, interdisciplinary, problem-driven field that addresses essential questions on the interactions between nature and society (Carpenter et al., 2009; Levin and Clark, 2010; Miller, 2015). Due to its close relation with natural systems, agriculture has a great responsibility in terms of sustainable use of resources, protection of rural communities, occupation, and human health. Concerning the origins of the term "sustainability", it was firstly introduced in forestry studies in the 18th century (Wiersum, 1995; Grober, 2007; De Luca et al., 2015a, 2015b). Since then, many definitions and theoretical framework have been proposed for sustainable agriculture too, but there is not yet consensus nor univocal set of practices. This is mainly due to the multifaceted functions and characteristics of agricultural systems themselves, which entail different typologies of impacts, among others:

- environmental (e.g. on soil, water, air quality, but also landscape, biodiversity, and other natural resources)
- economic (e.g. occupation, incomes, local development)
- social and cultural ones (working conditions, safeguard of cultural heritage, community livability, human health, local development).

Therefore, two main issues come into question in agricultural sustainability research: how to conciliate different disciplines of study, and how to take into account stakeholders' desiderata, i.e. reaching at the same time a scientific validity and a social acceptability?

In the last years, Life Cycle Assessment (LCA or eLCA), Life Cycle Costing (LCC) and social Life Cycle Assessment (sLCA), from the theoretical framework of Life Cycle Thinking (LCT), emerged as tools that enable comprehensive sustainability evaluations introducing the innovative perspective of the whole life cycle of products or services, in order to catch eventual burden shifts. Recently, Life Cycle Sustainability Assessment (LCSA), still under development, is representing the ‘step forwards’, resulted by the integration of the previous research experiences of LCA, LCC and sLCA studies.

Multi-Criteria Decision Analysis (MCDA) and participation methods are widely appreciated to balance and integrate these tensions allowing a holistic focus to decision making processes in complex contexts as it is agriculture (Britz et al., 2015; Bockstaller et al., 2015; De Luca et al., 2015b; Falcone et al., 2016). MCDA is here taken as the umbrella term for methods that enable to consider multiple conflicting criteria and to reach rational, justifiable and explainable decisions (Mendoza and Martins, 2006; Falcone et al., 2016). In addition, MCDA can provide objective means to include participative methods into decision processes (Brandt et al., 2013; De Luca et al., 2015b; Falcone et al., 2016).

Many scholars have combined the Life Cycle (LC) tools (alone or jointly) with different MCDA methods; indeed, as affirmed by Finkbeiner et al. (2010), life cycle evaluations can gain additional insights from MCDA e.g. by addressing scales of impact assessment, selection of sustainability indicators, and weighting and aggregation of indicator-specific results. Very often, participatory approaches have been successfully developed and applied, alone or through MCDA tools, in Life Cycle (LC) evaluations.

The purpose of the present study is to conduct a critical and systematic review of the life cycle studies that included MCDA and/or participatory approaches to complement or reinforce their effectiveness. In particular, the specific aim is to highlight how these tools were integrated or complemented, which assets have been gained and how stakeholders were involved.

2 Background and terminology

2.1 A recall to the main conceptions of sustainable agriculture

Since the publication of the milestone references by Meadows et al. (1972) "The limits to growth", the well-known Brundtland Report "Our Common Future" (WCED, 1987) and the Rio Conference (UNCED, 1992), sustainability and sustainable development (SD) became the catchwords of every field of research and the principal concern of policies and management strategies. Many conceptions of sustainability have been elaborated at academic level, such as:

- "weak sustainability" and "strong sustainability", concerning the substitutability of natural and constructed (artificial) capital in sustaining human well-being (Hartwick, 1977; Solow, 1986; Daly and Cobb, 1994);
- "carrying capacity", defined as the balance between resources consumption rates and the time for their regeneration (Daily and Ehrlich, 1992; Goodland and Daly, 1996); it is similar to the concept of "resilience", that is the capacity of a system (social, natural or others) to positively respond to changes and disturbance without modifying its initial state (Holling, 1973);
- the "systemic approach", stating that all living systems are in a relation of interdependence: what has to be sustained is not economic development, but the so-called web of life (Capra, 2002).

Actually, the most shared framework is the "Three Pillars" approach or "Triple Bottom Line" (Elkington, 1997) that distinguishes three dimensions of sustainability: economic viability, social equity and ecologic integrity. The assumption of separated dimensions allows the approach to be easily operationalized and to highlights trade-offs, especially in accounting and evaluation practices; for this reason, it is widely accepted by policy makers, included in many soft law documents and promoted within business management of companies (Bosselmann, 2008).

However, this approach has been strongly criticized from a scientific point of view, because these kinds of research/evaluation practices entail producing and balancing separate findings and relevant trade-offs, and the problem of how integrate them still remains open (Gibson, 2006).

Indeed, sustainability is an integrative concept (Gibson, 2006) due to the variety of possible epistemological commitments, theoretical frameworks and methodological practices of its different disciplinary roots (MacGillivray and Franklin, 2015). Solutions to sustainability problems are not obvious because “complexity is high, uncertainty is rampant, values are in dispute and trade-offs are the norm” (Miller, 2015:6).

Two main intellectual trends exist in sustainability management: an analytic school of thoughts that prioritize measurement and quantifications of problems; and a policy/management one, that prioritize long term changes, bottom up approaches, and stakeholder involvement. Even if these traditions share the common objective of providing sustainability solutions, they do not always interact and are sometimes work in opposite directions; however, they are both necessary and suitable, because sustainability requires at the same time the methodical identification and quantification of problems, proposals and incentives for change processes, as well as the involvement of stakeholders to include their values and interests in decisions for sustainable processes (Mulder, 2016). Therefore, the core issues of sustainability evaluations are balancing different tensions such as maintaining scientific credibility, assuring practical saliency and legitimizing the process to different addressees (Joice, 2003), in order to comply the multifaceted connotation of sustainability entails analytical, normative, and political aspects thereof people may prioritize one over another (Littig and Grießler, 2005; Mulder, 2016).

Concerning the analytical aspects of sustainability, many tools have been developed by scholars and are currently applied in different fields. Some of the methodologies that gained growing consensus are the methodologies belonging to the so-called Life Cycle Thinking conceptual framework, i.e. Life Cycle Assessment (LCA or eLCA) dedicated to the assessment of environmental impacts of the whole life cycle of a product or service, Life Cycle Costing (LCC) devoted to the accounting of all costs spread during the functioning of the life cycle, and the Social Life Cycle Assessment (sLCA) conceived to evaluate social impacts on different typologies of actors involved.

Concerning the normative aspects and the social acceptance of sustainability evaluation practices, participative methodologies for stakeholders' involvement are suitable and well developed in agricultural and rural contexts.

To cope with the multifaceted aspects of both sustainability and agricultural issues, to combine the above mentioned analytical and normative aspects of sustainability, and to integrate different - and sometimes conflicting - stakeholders' desiderata, MCDA methodologies are potentially the most appropriate, alone and in combination with other assessment tools (Baourakis et al., 1996; Hayashi, 2000; Siskos et al., 2001; Aznar et al., 2011; De Luca et al., 2015a, 2015b; Falcone et al., 2016; Hayashi, 2016).

2.2 The sustainability assessment of agricultural systems in a LC perspective

The quantification of sustainability performances of agricultural products become necessary when policies, marketing strategies and management processes are required to be oriented towards sustainability goals.

Life cycle methodologies are growingly gaining consensus in agricultural research as objective methodologies to identify different typologies of impacts (De Luca et al., 2015c). They are highly appreciated at academic level as well as in the practical field of management because of their effectiveness in the appraisal of the environmental, economic and social burdens of different agricultural systems; allowing also the comparison of different products, farming systems, pest managements, and so on (Milà i Canals, 2003, O 'Brien et al., 2012; Tuomisto et al., 2012; Notarnicola et al., 2015; Meier et al., 2015; De Luca et al. 2015c). And they well fit into sustainability discourses as tools that help to broaden the focus of analysis to the whole life cycle of a product or service, accounting for a wide variety of different typologies of impacts, and highlighting possible hot-spots and burden shifts (De Luca et al., 2015c).

LCA is aimed at quantifying environmental impacts, from "cradle to crave", deriving from many factors; energy consumption, climate change, ozone depletion, eutrophication, acidification, land use eco-toxicity and human toxicity are the most assessed impact categories in LCA, included agricultural studies (Meier et al., 2015; Cerutti et al., 2015; Gabel et al., 2016). LCC is considered its "economic peer", and it mainly consists in the account of all costs generated during each life cycle phase, more than an economic impact evaluation; it is frequently applied by companies to take decisions on major investments in relation to the whole life cycle of a product (Krozer, 2008).

Despite being the first life cycle tool to be developed, it is not yet standardized by specific norms, except for the building sector (ISO 15686-5:2008 and Norwegian standard NS 3454). Many approaches can be found in literature, such as the monetization of environmental qualities, the account of discounted costs of all life cycle (e.g. those imputable to the entrepreneur), and the evaluations of those risks, for companies, connected with regulations and liabilities that can be imposed by laws inspired by customers and citizens' claims (Krozer, 2008; Strano et al., 2013; Falcone et al., 2016). SLCA is the latest tool developed under the Life Cycle conceptual framework, and it is devoted to the assessment of all kind of impacts generated by the life cycle and affecting people (Zamagni et al., 2016). The methodology is not yet standardized, there is no consensus about the evaluation process, nor a unique definition exist for sLCA and social impacts. This led to a plethora of methodological proposals that can differ in many points, such as the perspective of the assessment, the source of impacts, what is worth to be assessed (the “impact categories” as called in the vocabulary of LCA) as well as the same epistemological underpinnings (Iofrida et al., 2016).

It is now well recognized that to realize more sustainable agricultural products it is necessary to overcome the sector-based perspective and to look for solutions to real-world problems through scientific and socially robust knowledge (Brandt et al., 2013), and LC methodologies appear to be promising tools to reach this goal (Klöpffer, 2014). Main characteristics and differences among LCA, LCC, and sLCA are highlighted in Table S1.

A wide variety of products have been assessed within the LC methodologies framework, with LCA as the most commonly applied; agricultural, forestry and food products gained great attention as well as biomasses for energetic purposes, industrial products, buildings and waste management (Cerutti et al., 2015; De Luca et al., 2015c). According to Notarnicola et al. (2015), conducting LC evaluations on food and agricultural products entails more methodological challenges than other typologies of products concerning for example the definition of the FU, the data collection, the inventory analysis (Bellon-Maurel et al., 2015), the modelling of exposure to pesticides and the dispersion of fertilizers, the effects on land and water use. This is due to their biological nature (that does not depend by the human control, as it is in industrial contexts) and their low-standardized processes, as well as the typology of farming system (organic, integrated or conventional), the local specificities (soil, climate, water quality), conditioning and retailing systems (Cerutti et al. 2015).

Few LCC applications can be found in agri-food and agricultural contexts (e.g., De Gennaro et al., 2012; Sanyé-Mengual et al., 2015, Tamburini et al., 2015; Christoforou et al., 2016; Stillitano et al., 2016; Falcone et al., 2015, 2016) probably due to the difficulty of adapting this technique to the complex characteristics of farming processes (De Luca et al., 2015b). Moreover, most of the studies available in literature are not stand alone assessments, but rather in association with other tools (Jeswani et al., 2010; Iotti and Bonazzi, 2014; Tamburini et al., 2015; Falcone et al., 2015, 2016).

As SLCA methodology is not methodologically well defined, fewer case studies can be found in literature compared to the other LC tools. However, among them, agricultural and food systems gained the most attention of scholars, as it has been the case of cut roses (Franze and Ciroth, 2011), orange juice (Benoît Norris et al., 2011), bananas (Feschet et al., 2013), tomatoes (Bouzid and Padilla, 2014), Fisheries (Mathé, 2014), clementine growing systems (De Luca et al., 2015c), milk production (Revéret et al, 2015) and many others (Zamagni et al., 2016).

The principal advantage of applying LC methodologies in agricultural, forestry and food evaluations remains about the possibility of considering the whole supply chain, highlighting burden shifts, comparing scenarios differing in terms of production techniques (e.g., conventional versus organic), products (e.g., comparison between different cultivars, or different agri-foods providing the same service) and so on (De Luca et al., 2015b).

2.3 MCDA and participation to foster agricultural sustainability assessment

Decision making processes become highly critical when decisions are complex, involve potentially high uncertainties, and different types of stakeholders are involved. Agricultural management is increasingly oriented to the use of the best management practices to reduce burdens on the environment, improve the quality of life and preserve the economic viability; to do this, many different criteria need to be included in the decision making process (Blanquart, 2009). The multifaceted connotation of agricultural sustainability is due at the same time to analytical, normative and political implications.

Being a socio-scientific subject and not only a question of natural resources management, agricultural sustainability implies balancing scientific credibility, assuring practical saliency and legitimizing the process to multiple stakeholders typologies (Joice, 2003). This is also the principal reason why the inclusion of stakeholders through participatory approaches in agricultural sustainability management would be suitable (Pretty, 1995; Reed et al., 2009; Brandt et al., 2013).

According to some authors (Becker et al., 1999; Littig and Grießler, 2005), when social impacts are also under scrutiny, the normative aspects of sustainability become quite imperative, because the discourse turns on which are the basic requirements of livability of a society, and which principles should be defended for the current and next generations. Pairwise, social sustainability should be guided by analytical concepts that enable understanding the relationship between society and nature; therefore, sustainability approaches and indicators should be based both on analytical clarity as well as socially accepted values (Littig and Grießler, 2005).

To support such complex decisions, MCDA is the most applied methodological framework, as it allows us to use both qualitative and quantitative approaches simultaneously that explicitly take into account multiple and often conflicting decision criteria (Adulin et al., 2014; Cinelli et al., 2014). There are different MCDA approaches, methods and techniques, but the common points of all of them are about the objective choice among a discrete or continuous set of alternatives (solutions, projects, actions), using two or more criteria, and the involvement of at least one decision-maker to evaluate, weight, rank, sort and choose among these alternatives (Roy, 1996; Doumpos and Zopoudinis, 2004; Figueira et al., 2016) (Table S2). In literature, many terminologies are used to describe this family of methods. For the purpose of this paper, the following definitions are assumed as synonyms: Multicriteria decision analysis (MCDA), Multiple criteria or multicriteria decision aiding (MCDM), Multiattribute utility theory (MAUT), Multicriteria optimization (MCO), Multiobjective decision making (MODM).

Concerning the inclusion of participation in agricultural decision making for sustainability purposes, it can consist in the involvement of many typologies of actors, and for different purposes. There are normative and pragmatic arguments supporting stakeholder engagement in environmental (and agricultural) management: normative claims concerns benefits for communities (e.g. preservation of democracy and equity), increase the trust in public policies and acceptability of management practices, empower actors through processes of social learning; pragmatic claims concern the quality and durability of decisions shared with stakeholders (Pretty, 1995; Reed, 2008; Binder and Feola, 2013; Myllyviita et al., 2013; Triste et al., 2014).

Stakeholder theory has been widely discussed in literature (Mitchell et al., 1997; Phillips, 2003; Friedman and Miles, 2006; Freeman et al., 2010). The core debate around the definition of stakeholder is about how to define a legitimate stake; however, the most shared definition is about those who affect or are affected by a decision or process or organization behavior (Reed et al., 2009). Value-chain actors, local actors, citizens or experts can be involved to acquire information or to build knowledge.

Following to Kruetli et al. (2010) and Brandt et al. (2013), it is possible to differentiate participatory approaches according to four degrees of intensity: information, consultation, collaboration and empowerment. These degrees are distinguished according to the degree of involvements of actors (the attitude of actors towards evaluation process), and the typology of evaluation approach (the attitude of the evaluation approach towards actors) (Figure S1):

- Information: actors provide input useful for the evaluation process, and/or receive information about sustainability issues;

- Consultation: actors are involved through more specific methods such as interviews and surveys, quantitative, qualitative, multicriterial methods; they are asked about their opinions, they acquire knowledge about the systems under evaluation;

- Collaboration: actors are more involved, actively participate into the evaluation process, they acquire knowledge about instruments and methodologies; the evaluation process is not detached from the context, it is rather modelled according to stakeholders' reality;
- Empowerment: actors are totally aware of the systems under scrutiny and own the evaluation process, which is co-constructed with them; they are enabled to make the evaluations process without any external intervention.

There is a wide variety of participatory methods, such as interviews, structured or semi-structured questionnaires, brainstorming, focus group, Delphi method, the nominal group technique, among others. MCDA are often applied for participatory purposes, for their suitability in conciliating different aims and solving conflicting ambitions. The specific method should be chosen according to the circumstances and the typology of actors to be involved: if participants are illiterate, simple methodologies are more appropriate (Reed, 2008); if high expertise is required, skilled experts can be involved through more complex methods, such as mathematical models (Kangas and Leskinen, 2005; Myllyviita et al., 2012, 2014). Informing appropriate knowledge about agricultural sustainability requires multi and transdisciplinary scientific research, entails uncertainties and diverse interests. Values, beliefs, social networks can shape the perception of stakeholders in the context of sustainable agriculture; in their research, scientists are called to engage with them, take into account the cultural and social context, and produce "actionable science", otherwise they could fail to guide adaptive responses (Bartels et al., 2013).

3 Critical review of life cycle studies combining MCDA and/or participative approaches

3.1 Material and methods

According to Grant and Booth (2009), a critical review is an extensive literature research with a critical evaluation of the main contributions, analyzing significant components, identifying the most significant differences, synthetizing the main concepts; a systematic review has the same characteristics, but seeks to systematically search, appraise and synthetize research evidences.

The aim of the present review methodology is to combine the strengths of these review typologies, and therefore systematically (according to predefined parameters) and critically (comparing results and extrapolating new information) highlight the following features:

- which participatory and/or multicriterial methods have been associated to LC tools (LCA, LCC, *s*LCA, LCSA);
- how they have been integrated or complemented (methodological relationships);
- the intensity of involvement of stakeholders (degree of participation);
- which synergies have been reached by combining the methods.

To serve these purposes, an evaluation matrix has been set up to systematically gather and critically synthetize research evidences, by classifying papers according to the year of issue, literature typology, topics or field of application, methodologies applied, and typology and intensity degrees of integrations.

The review methodology consisted in the implementation of multiple iterative steps, i.e. the results of each step allowed to develop the following one or to reconsider the previous ones; the protocol is synthetized in Table S3 and Figure 1.

Figure 1 - Methodological steps of the review process

Scientific literature published from 1997 up to August 2016 was gathered by means of scientific databases (Scopus and Science Direct), as well as dedicated social networks

(Research Gate, Academia) and other on line search engines (Google Scholar); only indexed references were gathered, while grey literature (reports, theses, readers) were discarded. The search was conducted by means of specific search terms in the fields "title", "abstract" and "keywords", concerning life cycle tools and with the help of Booleans operators, e.g. ("life cycle assessment" OR LCA), ("life cycle costing" OR LCC), ("social life cycle assessment" OR SLCA), (life cycle sustainability assessment" OR LCSA) NEAR/AND ("multicriteria" OR MCDA, MCDM, MCA, "multiple criteria", "multi-criteria") and other synonyms, ("participat*" OR "stakeholders involvement") and synonyms. When no one of the previous terms were displayed in the above mentioned fields of search, a speed reading was done looking for the terms within the text.

The inclusion criteria concerned the joint application (or methodological proposal) of a LC tool and a multicriteria or participative methods. exclusion criteria concerned the absence of a scientific citation index and the lack of characteristic elements of LC studies, such as the definition of a functional unit (FU), of the system boundaries, the four typical phases as they have been standardized by ISO norms in 2006 (goal and scope, inventory analysis, impact assessment, interpretation). Reviews or studies that did not provide sufficient elements to understand how evaluations methods were integrated or complemented were discarded too.

Table 1 shows the matrix parameters that allowed to highlight common elements and divergent features. During the papers classification, if noteworthy elements emerged, parameters (matrix's columns) were modified or adapted (iterative process).

Table 1 - Matrix parameters for the systematic and critical review

The first parameters are about the general characteristics. "Literature typology" refers to the editorial destination (only indexed scientific works were taken into consideration), while the "typology of study" refers to the general purposes: applicative, methodological or theoretical proposals; applicative studies are obviously methodological too but provide concrete results from hypothetical or real cases studies, while methodological studies only discuss evaluation proposals and theoretical studies discuss the scientific underpinnings of evaluations processes. The parameter "methodologies applied" briefly reports which LC methodology has been associated with a multicriterial and/or participative method; as previously explained, here MCDA is used as an umbrella term to indicate all typology of multicriterial method, later specified in a dedicated column of the matrix (see Supplementary Material). "Typology of integration" indicates how methodologies have been combined, integrated, complemented, or mixed, and then, details on which specific method has been used are given. Some other parameters are focused on typical features of LC methodologies (such as system boundaries, scenarios, functional units, categories of impact). During the reviewing process, it has been noticed that many studies also integrated other typologies of assessment indicators or methods different from MCDA or LC, such as Risk Assessment, Likert scaling, performance indexes, etc., so a further column of the matrix has been dedicated to these additional features. Two parameters are dedicated to the description of the "degree of integration" of LC/MCDA methodologies, and in particular if they are fully merged or maintained separated integrating just their results, and in which "phases of the research process" they are combined. A further section of the matrix is dedicated to the outlining of participative features, such as how many studies recurred to stakeholders' involvement, which actors, and which was the intensity of participation. Finally, the last columns of the matrix are dedicated to the advantages and disadvantages of the joined use of the methodologies, as affirmed by the same authors.

Once the matrix has been completed, input data were furtherly compared to highlight significant information or relationships.

3.2 Review results

The search of scientific publications through the above mentioned specific keywords, conducted until August 2016, resulted in a first group of 75 papers published from 1997 to 2016 (Table S4). Analyzing the number of publications per year (Figure S2), it is easily visible how the interest in combining the methodologies has been growing in the last decade, with a trend line described by the following equation (eq. 1):

$$y = 0.4964x - 0.6601 \quad \text{(eq. 1)}$$

The most significant peaks were in 2011, 2012 and 2015. Most of them (91%) are published in scientific journals, while only few are indexed conference proceedings (4%) or book chapter (5%); almost all studies are applicative case studies, with some exceptions of methodological proposals, theoretical argumentations (Seager and Linkov, 2008; Jeswani et al., 2010; Recchia et al., 2011b) and a review (Huttunen et al., 2014).

Concerning the parameter "fields of application", there is a great variety of products and services assessed, attesting the versatility and adaptability of LC and MCDA methodologies to the most diverse contexts, and their reliability in the scientific community as tools to accompany decision making processes. In particular, among the 75 papers of the early selection (Figure S3), 31% concerned agriculture and forestry-based products, above all biofuels and biomasses production for energy purposes, while 24% were about industrial products, 13% about methodological development concerns (specific LC phases or their development as decision-making tools). Wastes management (11%) gained also great attention by researchers, as well as building sector (7%) and vehicles (5%). Moreover, the trends of the most assessed products deserve some attention: industrial products showed a quasi-constant trend, while the agricultural and forestry-based products showed an increase (Figure 2). This is certainly due to the growing interest in renewable and alternative sources for energy production.

Figure 2 - Comparison of trends: agricultural and forestry-based products vs industrial ones

Once all the inclusion and exclusion criteria have been applied, the selection has been reduced to 22 papers (Table 2), published from 2007, when the first study on a forestry-based product was issued, to 2015; for a reason of homogeneity papers issued in the beginnings of 2016 were excluded. In 2011 a peak of publications is also due to the consideration, in the selection, of the chapters (4) from the same book by Recchia et al. (2011e). The studies selected are principally journal article (18 papers) published on various scientific peer review journals, among which the most recurring are *The International Journal of Life Cycle Assessment* and *The Journal of Cleaner Production*. Most of them are applicative studies (18), while the rest are purely methodological proposals, proving the interest in the practical implications of these methodologies. Undoubtedly, applicative studies are methodological as well, but the difference stays in testing the methodologies providing tangible solutions for real problems.

In terms of spatial dimensions of the assessments procedures applied in the 22 studies, there is some heterogeneity (Figure 6); indeed, most of the papers based the assessment at a regional (Recchia et al., 2011d; Čuček et al. 2011, 2012; Mathé, 2014; Pastare et al., 2014) or farm level (Recchia et al. 2011a, 2011b, 2011c; Castellini et al., 2012; De Luca et al., 2015b), followed by the local level (Lipušček et al., 2010; Recchia et al., 2010; Manik et al., 2013; De Luca et al., 2015a), the national level (Halog and Manik 2011; Ahmed et al., 2012; Ren et al., 2015), and supply chain level (Myllyviita et al., 2012). In the remaining papers more levels are applied at the same time (Hermann et al., 2007; Myllyviita et al., 2014) or are not at all specified (Zhou et al., 2007; Kralisch et al., 2013). However, it is necessary to point out that the territorial level here does not refer to where the impacts are spread, but to the territorial size of the system(s) under assessment.

Concerning the location of the studies, 64% of the 22 selected papers are located in Europe, while 27% in Asia and 9% in the American continent; among the European studies, 7 are located in Italy, 2 in Finland, and the rest in Latvia, France, Slovenia and Scotland.

Table 2 - Final list of selected papers

Going more in depth into the methodological characteristics of the studies gathered, LCA has been the most applied methodology (19 times) among LC tools, compared to LCC and sLCA (6 times each one). This predominance was already revealed in the first selection (75 papers) where 84% of studies applied LCA, 14% LCC and 6% sLCA. This is not surprising, as environmental burdens are the principal concern in most of sustainability studies and policies, and LCA is one of the most accredited accounting tools worldwide. Some authors applied all LC methodologies presenting their proposals as Life Cycle Sustainability Assessment; however, for the purpose of this review, we considered the tools separately. Indeed, in the studies selected, LCSA is never a hybrid methodology, but presented as a sum of methodologies (Ren et al., 2015), such as for example LCA+LCC+sLCA = LCSA (according to Klöpffer, 2008; Sala et al. 2013a, 2013b), or integrating some other methodology or indicator in a life cycle perspective (e.g. Zhou et al., 2007).

LC tools were not the only impact assessment procedures applied for environmental, economic and social purposes; many others have been integrated, such as GIS (Recchia et al., 2010), footprints (Čuček et al., 2011, 2012; Castellini et al., 2012) cognitive mapping (Myllyviita et al., 2014), performance indexes (Hermann et al., 2007), and many others (see Supplementary Material).

Concerning the multicriterial methods implemented in the studies, 20 papers combined the MCDA with LC evaluations, some of them with participatory purposes, while just two papers combined only a non-multicriterial participative methodology to a LC study (Manik et al., 2013; Mathé, 2014). As reported in Table S5, the most combined multicriterial method was the AHP (Analytic Hierarchy Process) by Saaty (1990), applied in eight studies. Other MCDA methods applied were SMART (Simple Multi-Attribute Rating Technique) and MINLP (Mixed-integer nonlinear programming model), with two studies per each methods, VIKOR (VIseKriterijumska Optimizacija I Kompromisno Resenje) by Opricovic (2009), ELECTRE (ELimination Et Choix Traduisant la REalité) by Roy (1968), PROMETHEE (preference ranking organization method of enrichment evaluation) by Brans and Mareschal (1990), TOPSIS (Technique of Order Preference Similarity To Ideal Solution) by Hwang and Yoon (1981), and others. Some authors declared to use a multicriterial approach, but did not refer to any standardized or specific MCDA method, as it is the case of Recchia et al. (2011a; 2011b; 2011c; 2011d). It is noteworthy to specify that 6 papers applied MCDA specifically for participatory purposes, such as LipuščČek et al. (2010), Halog and Manik (2011), Myllyviita et al. (2012), Pastare et al. (2014), De Luca et al. (2015a, 2015b), while other authors preferred to delegate the participative feature to non-multicriterial methods, such as interviews, surveys, questionnaires, cognitive mapping or fuzzy theory applications, and to reserve MCDA methods only for impacts evaluation purposes (Castellini et al., 2012; Manik et al., 2013; Mathé, 2014; Myllyviita et al., 2014; Ren et al., 2015).

Concerning the combination of the methodologies (Table S6), it has been possible to distinguish four main typologies of integrations, which have been ascribed to the following groups:

- “MCDA<LC”: multicriterial analyses are applied as a part of a LC framework, to complement the significance of evaluations results, or to allow the combination or synthetization of different typology of insights;
- “LC<MCDA”: LC results are considered, even with other methodologies, as part (indicators) of a wider multicriterial framework;
- “LC_MCDA”: both methodologies are on the same level and have the same importance: they are fully merged;
- “participation<LC”: one or more participation methods (multicriterial or not) are applied with the purpose of complementing LC results with stakeholders’ values and giving more legitimation to insights.

During the review process, a further distinction has been made according to the typology of integration: indeed, in some cases methods have been fully integrated.

The most common typology of combination has been represented by the second group, “LC<MCDA”: 50% of studies gathered used one or more LC methodologies to assess the environmental, economic or social issues of a system (or scenarios) to be integrated in a wider framework. Six studies from this group involved stakeholders into the assessment process, mainly with a consultation role.

Concerning the group “MCDA<LC”, it represented 23% of studies, of which 3 papers also involved stakeholders (Myllyviita et al., 2012; De Luca et al., 2015a; Ren et al., 2015). Studies belonging to this group used MCDA as a secondary element, to add more information to a stand-alone assessment process.

A third group of studies (18%) applied both typologies of methods as a hybridized one, i.e. merging them into a unique research process: each method could not stand alone for the purposes of the evaluations (Hermann et al., 2007; Halog and Manik, 2011; Čuček, et al., 2011; Ahmed et al., 2012).

Finally, only two papers combined a non-multicriterial participation method to sLCA (Manik et al., 2013 and Mathé, 2014), with the specific purpose of involving specific groups of stakeholders; indeed, these were the studies where actors were involved with a higher intensity degree (consultation and collaboration).

Paying attention to the participative aspects, 54% of papers involved stakeholders into the evaluation process, and half of them applied a MCDA tool specifically for this purpose. According to the classification of stakeholders involvement made in section 2.3, all participative studies (12) involved actors as consultants, and in six cases they were involved to actively collaborate in the research process; two studies involved stakeholders also for information, while no one of the studies involved stakeholders at the empowerment level. The most applied MCDA method for participatory purposes was the AHP, followed by SMART and TOPSIS; in some cases these methods were accompanied by other participative methods, such as interviews (Pastare et al., 2014), Delphi (Lipušček et al., 2010; De Luca et al., 2015b). Most of the actors involved through participatory approaches were experts (41% of studies), such as scientists (Castellini et al., 2012), panelists (Myllyviita et al., 2012), entrepreneurs (Pastare et al., 2014), privileged witness (De Luca et al., 2015a, 2015b). Many authors preferred experts contribution because of their experience and capability to objectively compare sustainability impacts of systems, instead of presenting subjective opinions (Myllyviita et al., 2014).

Table 3 synthetizes the principal insights of the review, according a general framework of research process when assessing the impacts of system, i.e.: identification of scenarios, identification of impact categories or criteria, impact assessment, weighting and scoring, ranking and rating and stakeholders involvement, if any. Each paper (identified by an ID number) has been grouped according to the typology of methods integration applied; then, it has been described which tool or method has been applied per each phase of the research process. MCDA has been used to identify scenarios to be assessed by Recchia et al. (20110; 2011a, 2011b, 2011c, 2011d), while Ahmed et al., (2012) declared to identify the scenarios according to a literature review. Many authors recurred to participatory approaches to identify impact categories or criteria; the most applied methods were focus groups, Delphi, conceptual mapping, interviews, SNT, and only in two cases to MCDA (Myllyviita et al., 2012; Ren et al., 2015). Impact assessments have been mainly dominated by the application of LC tools and other methodologies (GIS, risk assessment, footprints, performance indexes, etc.); only Ahmed et al. (2012) applied a combination of GIS and AHP for evaluation aims. Almost all papers used a MCDA method for the weighting and scoring phase (the very strength of this family of methods), except for Čuček et al. (2011) who did not implement a weighting, and Manik et al. (2013) and Mathé (2014) who recurred to non-multicriterial participation methods for this research phase. MCDA methods were also applied for ranking and rating phases, especially AHP, PROMETHEE, ELECTRE, VIKOR, TOPSIS, SMART, and MINLP.

Table 3 - Characteristics of the typology of methods integration according to the main research phases

Despite the diversity of typology of integrations, there are many points in common concerning the use of LC and MCDA methodologies in the research phases and the synergies obtained. LC tools are preferred to obtain information on specific impacts, while MCDA are preferred for scoring and weighting, allow the integration of different typologies of information and can be used to take into account stakeholders' desiderata and directly involve actors into the evaluations. The synergies obtained can be useful in decision making processes.

4 Discussion

Insights from the review confirmed which assets can be reached by combining LC and MCDA methodologies and/or participation. The advantages are reciprocal (Figures 3 and 4). Firstly, LC tools, that can be considered multicriterial decision-making tools themselves (Chevalier and Rousseaux, 1999), can provide to MCDAs both punctual and global information on how to reduce negative impacts and avoid burden shifts; they are currently some of the most applied methodologies in product development, corporation marketing (e.g. by means of labels) because of their usefulness for decision-making processes (Kobayashi et al., 2015). Some LC methodologies are still under development (e.g. sLCA) and alignments issues among them are discussed at academic level (e.g. for LCSA), but the interest is growing because of their efficiency in finding main burdens contributors, that are not always evident, and simplified methods have been set up to keep the practicability to the broad public. Furthermore, according to Myllyviita et al. (2016), when dealing with sustainability assessment, MCDA alone is not sufficient to provide objective and definite answers and inputs from other tools and methods are needed to provide reliable impact assessments.

Figure 3 - Advantages from the integration of LC evaluations into MCDA

Secondly, MCDA methods can help LC practitioners (Figure 4) in dealing with subjective assumptions that are commonly considered as weaknesses of LC evaluations. The choice of scenarios to be assessed, of the functional unit, of the categories of impact to be included and the interpretation of results are some of discretional points of LC methodologies. Further benefits of using MCDA include a clearer distinction between objective and subjective elements of LC evaluations, and facilitate the collaboration with different stakeholders

(Gaudreault et al., 2009). Normalization, elicitation techniques, weighting and providing background information (typical elements of MCDA) have a great impact of the final results in LC evaluations (Myllyviita et al., 2014). Even more, MCDA can help in dealing with different typologies of sustainability insights that are often incommensurable such as environmental, economic and social issues (Myllyviita et al., 2016): as an example, when aggregating different typologies of dimensions, system boundaries can be misaligned, or trade-offs can occur, making more difficult the aggregation of results and the final interpretation. MCDA methodologies enable to include subjective values in an objective manner that the scientific reliability is not affected. Potential trade-offs between indicators, results, sustainability domains can be taken into consideration and solved by means of normalization, weighting, scoring, ranking, that are typical elements of multicriterial approaches (Benoit and Rousseaux, 2003; Myllyviita et al., 2012; Huttunen et al., 2014).

Thirdly, LC methodologies can take advantages from the integration of participatory tools (Figure 4). Stakeholders can provide information (primary data) and knowledge that enable researchers to better define topical elements of the systems under scrutiny; they can enable researchers better orienting the objectives of evaluations practices for decision making and widening the scope of social dimension. And, symmetrically, stakeholders can be empowered by learning about the consequences of decisions and actions (Huttunen et al., 2014).

Figure 4 - Advantages from the integration of MCDA and/or participatory tools into LC evaluations

Finally, as sustainability is a trans- and interdisciplinary issue, and involves high societal stakes and values, an epistemological eclecticism is unavoidable (Iofrida et al., 2016). Therefore, the pretention of a merely analytical assessment is quite unsuitable, and the consideration of stakeholders' values is no longer considered a scientific weakness, but has its recognized scientific realm in the interpretivism-oriented paradigms (Iofrida et al., 2016). MCDA are the most appropriate tools to objectively deal with subjective values choices (Buchanan and Henig, 1998). The same ISO norms 14040-44 (2006) ask practitioner to document every assumption, and in general it is recommended to start LC evaluations with stakeholders input when possible (Fullana i Palmer et al., 2011; Freidberg, 2015). In Table 4 are resumed the main reflections about LC and MCDA tools derived from the review.

Table 4 - Comparison of the main features of LC tools and MCDA

Concerning the advantages declared by the same authors of the papers reviewed (see Supplementary Material), most of them confirmed to have gained, through the combination of methodologies:

- comprehensiveness, facilitation of decision-making, easily readable insights (Herman et al., 2007; Pastare et al., 2014);
- unbiased decision support in case of contradictory effects (Kralish et al., 2013);
- the integration of knowledge from social and natural sciences (Halog and Manik, 2011; De Luca et al., 2015b);
- adaptability of their assessment model to other contexts (Lipušček et al., 2010);
- the consideration of a plurality of stakeholders' interests and the integration of local knowledge (Manik et al., 2013; Mathé, 2014; De Luca et al., 2015a);
- new perspectives and more comprehensiveness into LC evaluations (Myllyviita et al., 2012);
- a clearer view of the most suitable solutions (Recchia et al., 2011b);
- how to easily overcome conflicting values (Falcone et al., 2016).

5 Conclusions

Current agricultural management discourses are mainly focused on the transition to circular economy, on the promising production and use of renewable energies, i.e. residual biomasses and dedicated crops occupying every year more surfaces (Petrini et al., 2016), on the request for increasing yield due to population growth but also on conservative agriculture (Craheix et al., 2016) and the demand for food with "new" qualities such as fairness, safety and equitability from conscious consumers. All of these choices entails changes that have consequences, therefore evaluation tools are highly requested to justify and verify what risks to be more a "belief" than a scientific truth.

LC methodologies have gained a great consensus in agricultural sustainability assessment research. Compared to other tools, their assets stay in the widened perspective of assessment (each phase of the life cycle), to introduce a long term perspective, a global focus on consequences and the possibility to catch burdens shifts.

MCDA are widely recognized as supporting tools for decision-making, when dealing with conflicting alternatives and complex contexts and values are needed to be included (French and Geldermann, 2005). They are commonly considered as tools for preference measurement both in discrete choice set up, with limited amount of alternatives, and in continuous set up with infinite alternatives (Myllyviita et al., 2016).

The review conducted until August 2016 allowed to gather 75 studies that, in many different ways, combined LC evaluations with MCDA and/or participatory approaches. Among them, the authors of the present paper made a selection of studies about agricultural and forestry-based products assessments published between 2007 and 2015. The studies were critically and systematically reviewed according to a list of parameters that allowed highlighting the principal assets and synergies achievable by combining the methodologies. Results showed how the interest in this hybridization of methods has been growing in the last years, especially concerning agricultural and forestry-based products. Most of the papers, published in scientific journals, were represented by applicative studies, showing a practical interest in real study cases. The main typology of integration was represented by MCDA frameworks integrating LC evaluations.

Concerning the participative aspects, 54% of papers involved stakeholders into the evaluation process, and half of them applied a MCDA tool specifically for this purpose.

LC tools can provide to MCDAs both punctual and global information on how to reduce negative impacts and avoid burden shifts; MCDA methods can help LC practitioners to deal with subjective assumptions in an objective way, to take into consideration actors' values and to overcome trade-offs among the different dimensions of sustainability. These synergies are of utmost importance towards the development of new integrative assessment tools such as LCSA.

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Table 1 - Matrix parameters for the systematic and critical review

Parameters	*Description and examples*
# ID paper, authors, year, title, source	Identification of each paper selected for the reviewing process. The sequence follows the alphabetical order of authors' names. Each paper is identified by its bibliographical reference.
Literature typology (LT)	Journal Article (JA), Book Chapter (BC), Conference Proceedings (CP).
Typology of study (ToS)	Applicative (A), Methodological (M), Theoretical (T).
Place	Where the study is located.
Territorial dimension (level of assessment)	Global, national, regional, local, farm-based, etc.
Field of Application	What is the object of assessment (agricultural product, industrial items, building sector, waste management, etc.)
Scenarios	Concrete situations under assessment, eventually compared (organic vs conventional, technologies comparison, etc.)
Methodologies applied	MCDA and synonyms, LCA, LCC, SLCA, LCSA, etc.
Typology of integration (ToI)	LC methodologies applied as part of a multicriterial framework, MCDA applied to improve LC methodologies, etc.
MCDA and/or participation methods	Which multicriterial methodologies have been applied, which participative tools, and if they coincided (i.e. AHP, GIS-based tools, TOPSIS, ELECTRE, etc.; Delphi, focus groups, etc.)
LC indicators or categories	GWP, water depletion, ecotoxicity, etc.
LC functional unit	Units of assessment applied (1 kg, 1 hectare, 1 MWh, etc.)
LC system boundaries and/or phases	Cradle to crave, etc.
Other methods or indicators (different from LC and MCDA)	CBA, GIS, economic indicators, etc.
Degree of integration	Integration of processes or final results
Phase of research process	In which phase of the research process methodologies have been associated/integrated
Participation method	Which method has been applied to involve actors, and if it coincide with the MCDA applied
Typology of actors involved	E.g. local experts, scientists, consumers, workers
Degree of participation	Information, consultation, collaboration, empowerment
Advantages and objectives of integration approach	Assets obtained by integrating the methodologies, as affirmed by authors
Disadvantages or issues	Issues met by integrating the methodologies, as affirmed by authors

Table 2 - Final list of selected papers

# ID paper	*Reference*	**Methodologies applied**	**Typology of integration**	**MCDA methods**	**Participation methods**
1	Ahmed et al. (2012)	Feedstock assessment, LCA, spatial analysis with MCDA (GIS and AHP)	LC_MCDA	Spatial analysis (GIS-MCDA); AHP	None
2	Castellini et al. (2012)	MCDA, LCA, ecological footprints, emergy analysis, participation	LC<MCDA	ANOVA, Definite software, ELECTRE I	Interviews
3	Čuček et al. (2011)	MCDA, LCA, footprints	LC_MCDA	Mixed-integer nonlinear programming model (MINLP)	None
4	Čuček et al. (2012)	MCDA, LCA, footprints	LC<MCDA	Mixed-integer nonlinear programming model (MINLP)	None
5	De Luca et al. (2015a)	SLCA, (LCA and LCC as indicators), MCDA, participation (AHP, focus groups)	MCDA<LC	AHP	Focus group, AHP
6	De Luca et al. (2015b)	LCA, LCC, SLCA, MCDA (AHP), focus groups, Delphi, Q-methodology	LC<MCDA	AHP	AHP
7	Halog and Manik (2011)	LCA, LCC, SLCA, AHP, Data Envelopment Analysis (DEA), Sustainability Network Theory (SNT), integrated through System Dynamics (SD), Agent-Based Simulation (ABS)	LC_MCDA	AHP	AHP
8	Hermann et al. (2007)	LCA, AHP, Environmental Performance Indicators (EPIs)	LC_MCDA	AHP	None
9	Kralisch et al. (2013)	LCA, Environmental, Health and Safety Risk Assessment (EHS), LCC, MCDA	MCDA<LC	PROMETHEE II	None
10	Lipušček et al. (2010)	LCA, Delphi, AHP	LC<MCDA	Multi-attribute model; AHP	Delphi, AHP
11	Manik et al. (2013)	SLCA, participation	Participation<LC		Surveys
12	Mathe (2014)	SLCA, participation	Participation<LC		Focus groups, surveys
13	Myllyviita et al. (2012)	LCA, MCDA, participation	MCDA<LC	Simple Multi-Attribute Rating Technique (SMART)	Questionnaires and Simple Multi-Attribute Rating Technique (SMART)
14	Myllyviita et al. (2014)	LCA, MCDA	LC<MCDA	Simple Multi-Attribute Rating Technique (SMART)	Interviews, Conceptual Content Cognitive Map (3CM)
15	Pastare et al. (2014)	LCA, MCDA, participation and economic, technical and social indicators	LC<MCDA	TOPSIS, AHP	AHP, TOPSIS, questionnaires
16	Recchia et al. (2011a)	MCDA, LCA	LC<MCDA	"Intra criteria" method: Environmental Impact Assessment (EIA) and economic criteria	None
17	Recchia et al. (2011b)	MCDA, LCA	LC<MCDA	"Intra criteria" method: Environmental Impact	None

				Assessment (EIA) and economic criteria	
18	Recchia et al. (2011c)	MCDA, LCA	LC<MCDA	"Intra criteria" method: Environmental Impact Assessment (EIA) and economic criteria	None
19	Recchia et al. (2011d)	MCDA, LCA	LC<MCDA	"Intra criteria" method: Environmental Impact Assessment (EIA) and economic criteria	None
20	Recchia et al. (2010)	MCDA, LCA	LC<MCDA	Logistics, economic and environmental indicators	None
21	Ren et al. (2015)	LCA, LCC, SLCA, MCDA (VIKOR + AHP)	MCDA<LC	Fuzzy theory, AHP, VIKOR	Fuzzy Theory
22	Zhou et al. (2007)	MCDA, LCC	MCDA<LC	Sustainability index definition: mathematical matrix	None

Table 3 – Characteristics of the typology of methods integration according to the main research phases

Total num.	ToI	*# ID paper*	Identification of scenarios	Identification of impact categories or criteria	Impact assessment	Weighting & Scoring	Ranking and rating	Degree of stakeholders involvement, if any	Notes
5	MCDA<LC	*5*		Participation with focus groups	sLCA indicators (included LCA, LCC)	Participation with AHP	AHP	Consultation, collaboration	
		9			LCA, Environmental, Health and Safety Risk Assessment (EHS), LCC	PROMETHEE II	PROMETHEE II		
		13		Participation with MCDA	LCA	Participation with MCDA		Consultation, Collaboration	
		21		MCDA	LCSA	AHP	VIKOR	Consultation, collaboration	
		22			LCC, LCA	MCDA			
11	LC<MCDA	*2*			LCA, ecological footprints, emergy analysis	Participation with MCDA (ELECTRE I)	ELECTRE I	Information, consultation	
		4			LCA, total footprints	MINLP			
		6		Experts participation with focus groups, Delphi, Q-methodology	LCA, LCC, sLCA	AHP	AHP	Consultation	
		10			LCA	Delphi, AHP	AHP	Consultation	
		14		Participation: Conceptual Content Cognitive Map (3CM)	Economic, ecological, social and cultural indicators in a LC perspective	Participation: Simple Multi-Attribute Rating Technique (SMART)	Participation: Simple Multi-Attribute Rating Technique (SMART)	Consultation, Collaboration	
		15			LCA, economic, technical and social indicators	AHP, questionnaires	TOPSIS	Consultation	
		16	MCDA, Environmental Impact Assessment, economic indicators		Enviromental Impact Assessment, LCA, economic indicators	MCDA			MCDA consisted in the joint application of local economic and environmental indicators to choose the scenarios to evaluate through LCA. Therefore, MCDA is here applied “ex ante”.
		17	MCDA, Environmental Impact Assessment, economic indicators		Environmental Impact Assessment, LCA, economic indicators	MCDA			

		18	MCDA, Environmental Impact Assessment, economic indicators		Environmental Impact Assessment, LCA, economic indicators	MCDA			
		19	MCDA, Environmental Impact Assessment, economic indicators		Environmental Impact Assessment, LCA, economic indicators	MCDA		Consultation	
		20	MCDA, Logistics, economic, environmental indicators		Logistics, economic, environmental indicators, LCA	MCDA			
4	LC_MCDA	*1*	Literature review		Feedstock assessment, LCA, spatial analysis with MCDA (GIS and AHP)	AHP			The comparison ranking has been made by the modeler alone.
		3			Carbon FP, energy FP, water FP, water pollution FP, land FP, food-to-energy FP, social FP		MINLP		At the first level (MINLP-1) different footprints are obtained by the maximization of profit. Different sets of Pareto optimal solutions, one for each footprint, are generated at MINLP-2 as 2-dimensional projections of a multi-dimensional problem.
		7		Pareto principle, Sustainability Network Theory	LCA, LCC, sLCA, Data Envelopment Analysis (DEA), GIS, uncertainty analysis, System Dynamics	Participation with AHP and Agent Based Modelling	AHP	Consultation	
		8			LCA, Environmental Performance Indicators (EPIs)	AHP	AHP		
2	Participation< LC	*11*		Literature review	sLCA	Experts and stakeholders survey		Consultation, collaboration	
		12		Participation (interviews and focus groups) and literature review	sLCA	Participation		Information, Consultation, collaboration	

Table 4 - Comparison of the main features of LC tools and MCDA

	LC evaluations	MCDA
Purpose of the analysis	Assess the impacts of a product or service along its whole life cycle.	To evaluate a set of alternatives, taking into account multiple criteria and their relative weights.
Methodological process	Goal and scope definition, inventory analysis, data gathering, impact assessment and interpretation.	Problem structuring, criteria identification, scoring and weighting, ranking alternatives, uncertainty and sensitivity analysis, final recommendations according to results
Principal insights	A set of scores for a number of impact categories.	Aggregated evaluation criteria in a final score.
Advantages	Prevent burden shifts, completeness through 'cradle to grave' approach, comparisons of alternative product, services or scenarios.	Possibility of weighting the criteria, use of criteria with their own dimensions, single score for overall evaluation.
Weaknesses	Complex process that requires considerable time and data input; assumptions to be made; difficulties in alignment of different typologies of results.	MCDA often relies on input from experts and stakeholders; weighting can be subjective.

Source: Herman et al. (2007), modified.

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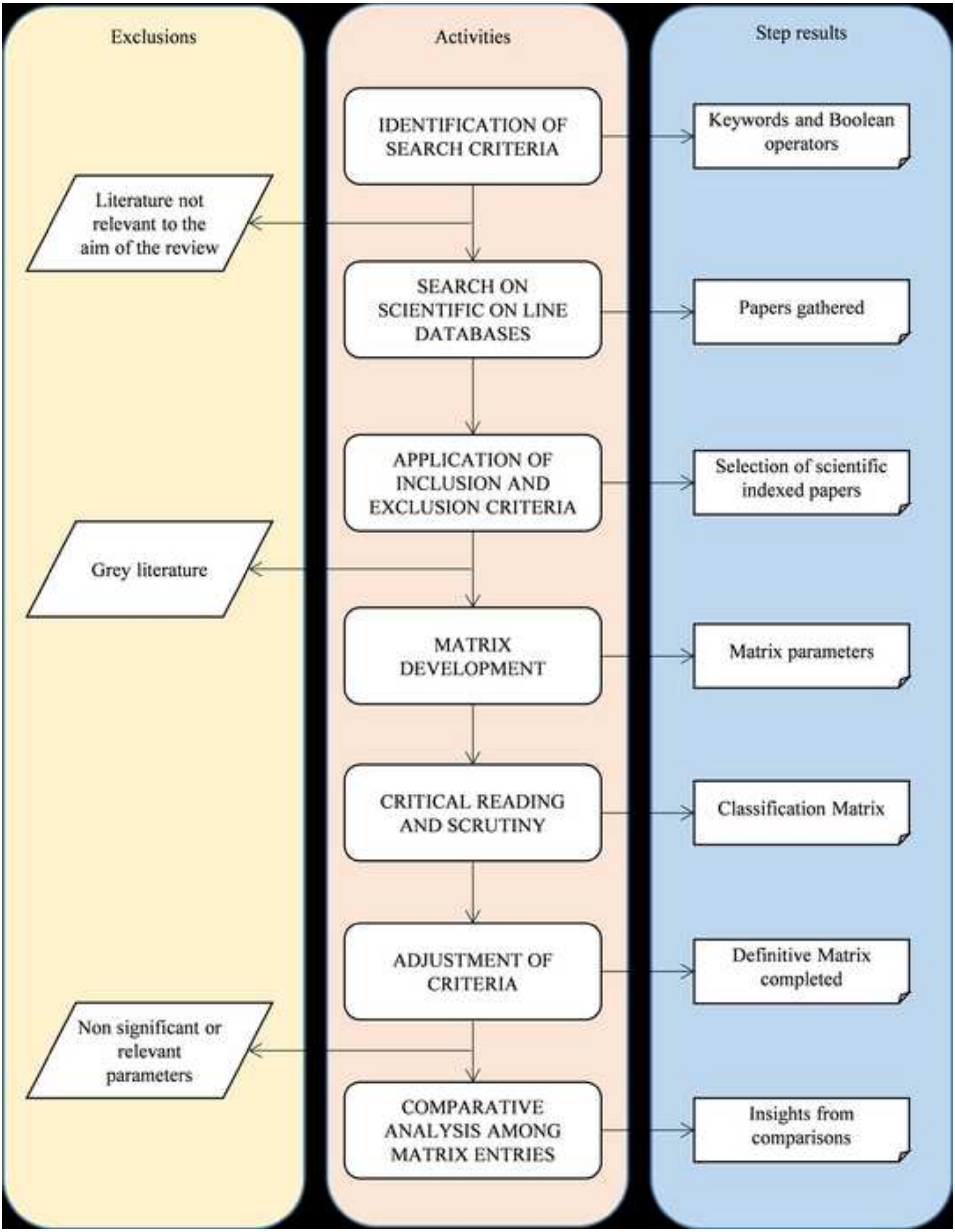

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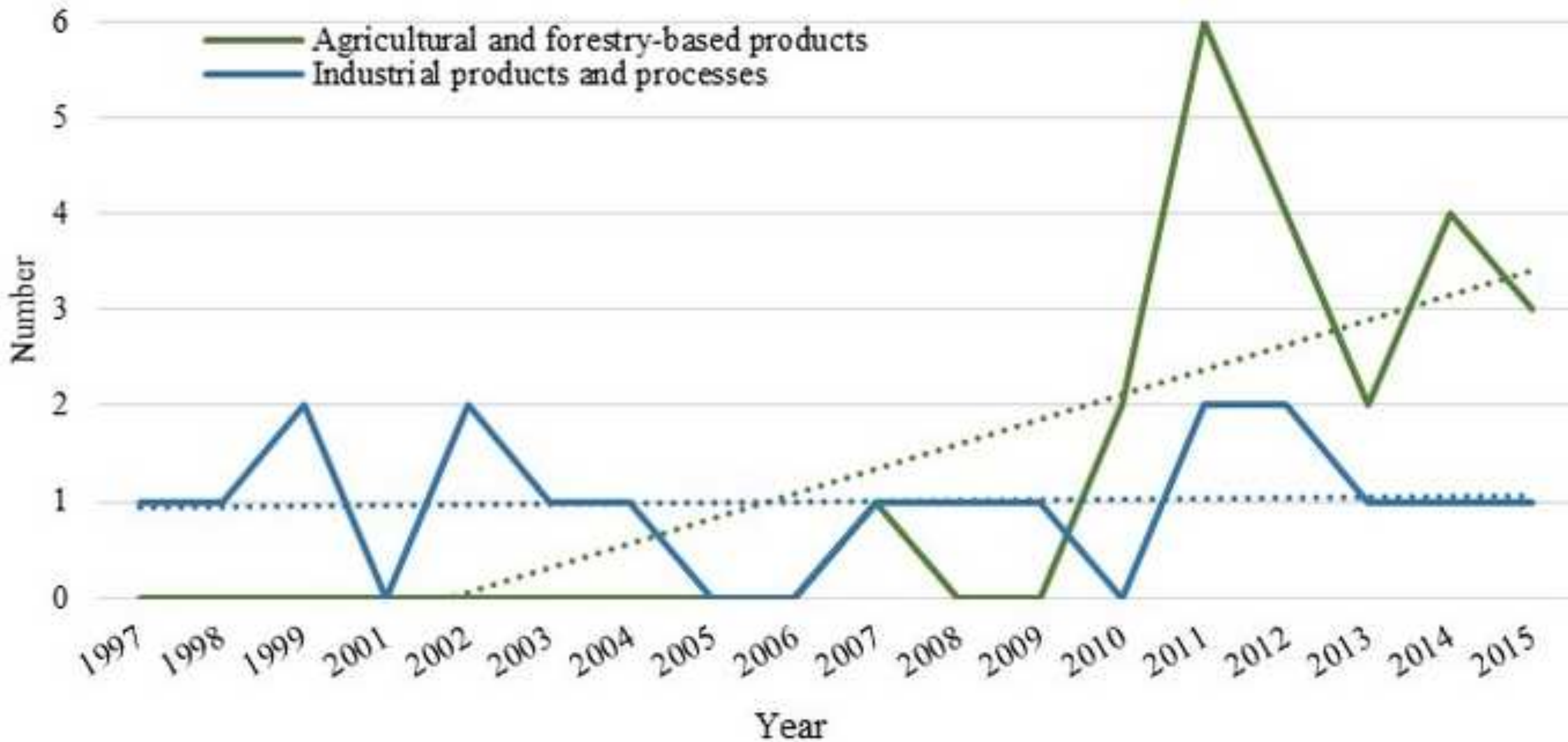

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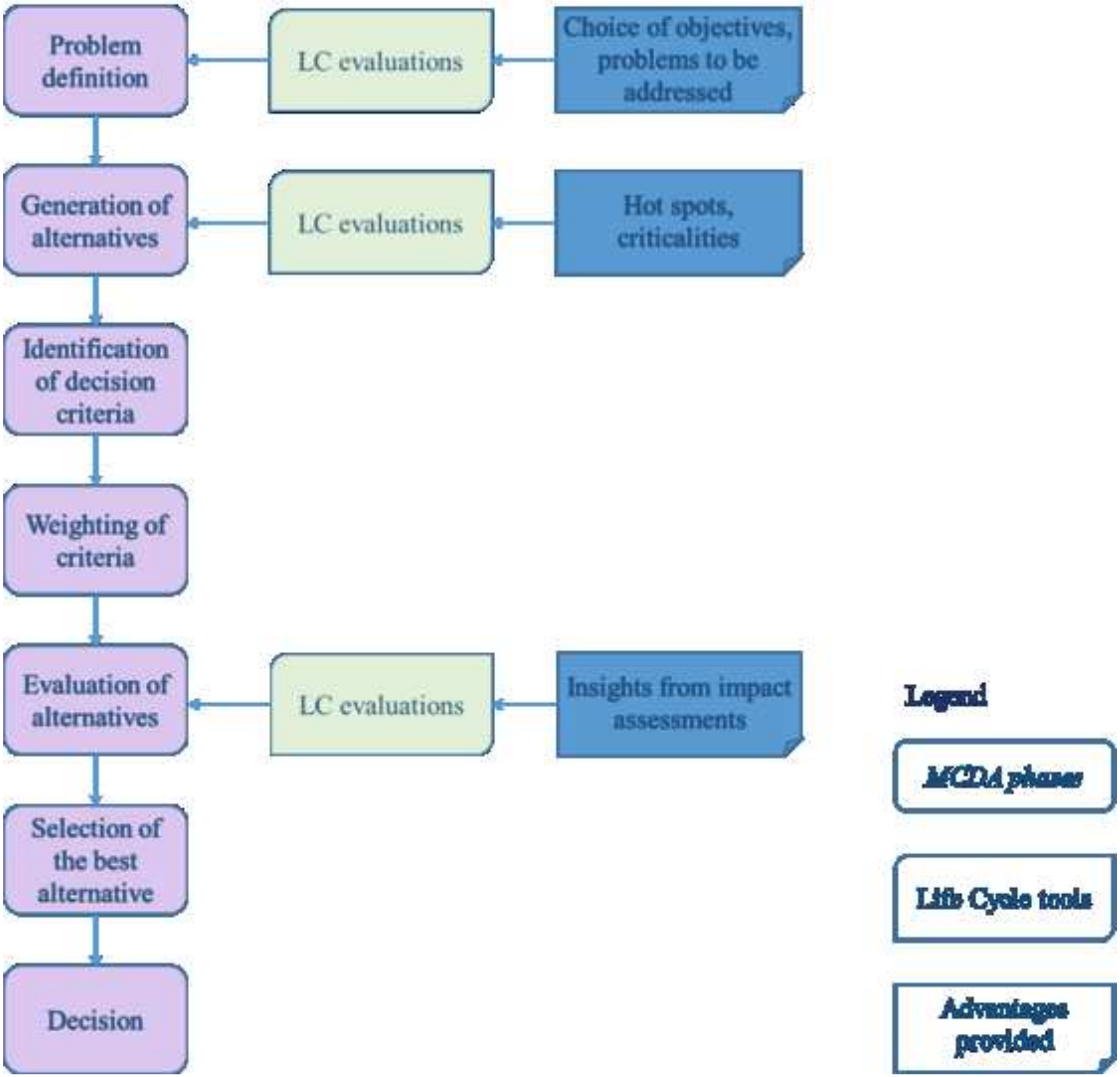

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