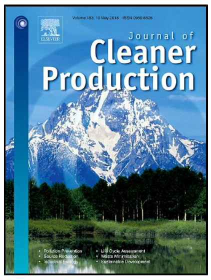

Life cycle assessment and eco-innovations: what kind of convergence is possible?

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Life cycle assessment and eco-innovations: what kind of convergence is possible?

Keywords: eco-innovation; life cycle assessment; ecological crisis; environmental impacts; natural resources; sustainable consumption and production

Abstract

Generation of goods and services are highly dependent on the use of natural resources. Until very recently, there was an implicit belief that the physical expansion of the economic system could be unlimited, as if the planet would have conditions and time enough to recover and continue to supply resources. This belief implies a confidence in an economic system that would provide whatever is necessary for a continuous growing production and consumption. Even believing that technology alone is not enough to solve the current environmental problems, it is certain that it can collaborate to mitigate climate change and to adaptation to changes in the environment. By bringing environmental aspects into discussions, eco-innovations can affect and transform the innovation system in order to create sustainable processes. However, the main challenge towards the transition to a more sustainable, cleaner and more equitable society is to set innovation in a new context, as until very recently it only considered the economic variables. This change means to value the social and environmental dimension of the innovation. In addition to eco-innovation, Life Cycle Assessment (LCA) is spreading in the industrial environment, offering promising perspectives. LCA is considered a valuable methodology in the environmental sustainability of industry. In this context, the present study addresses LCA and its relationship with the generation of eco-innovations. Drawing on contributions from literature on eco-innovation and LCA, the paper analyses available evidence on this relationship in a context of the transition towards sustainable development. To structure the debate, the paper offers a conceptual approach and an illustrative case on international researchers' and practitioners' perceptions on the potentially positive relationship between eco-innovation and LCA. The study gathers data in the Web of Science (WoS) Core Collection and in Scopus, in order to provide a picture of the distribution of documents retrieved from these databases, dealing with both eco-innovation and LCA topics. The paper concludes that the convergence of the eco-innovation and LCA studies is quite plausible, but at least in its initial phase, the literature that unites both themes is scarcely found in publications in the area of innovation, being more frequent in the area of engineering and management that usually addresses LCA studies.

1. Introduction

Generation of goods and services are highly dependent on the use of natural resources. Until very recently, there was an implicit belief that the physical expansion of the economic system could be unlimited, as if the planet would have conditions and time enough to recover and continue to supply resources. This belief implies a confidence in an economic system that would provide whatever is necessary for a continuous growing production and consumption. The transformation of natural resources into consumer goods necessarily implies diminishing the stocks of planetary resources (clean water, air, minerals, trees, plants, animals, etc.), polluting the environment throughout the production process, consumption and discarding. Since the industrial revolution, the productive process has run its course, without concern for planetary limits, until the exponential increase of production and consumption beginning in 1950 raised the alarms. That year was the starting point of the so-called Great Acceleration (Steffen et al., 2004, 2015), 'when all forms of consumption and degradation started to increase exponentially' (Léna and Issberner, 2016, p. 2). Global warming, rising sea levels, ocean acidification, biodiversity loss, deforestation, and the emergence of islands of pets and plastic in the Pacific are all consequences of human activity (IPCC, 2015), whose magnitude has led stratigraphists to consider that we are living in a new age, the Anthropocene (see Steffen et al., 2007).

The idea of planetary limits and the impacts of human beings' activities on Earth system was investigated in an increasing number of scientific works in the sixties, accompanied by the eruption of several environmental movements in many parts of the world. In 1972, finally, the environmental theme entered in the international agenda with the first United Nations Conference on the Human Environment in Stockholm. Since then, the environmental question has been discussed in numerous international meetings but with advances far short of what is necessary. The most recent annual survey conducted by Global Footprint Network (WWF, 2016)[1] indicates that there is an increasing consumption of natural resources on the planet. This survey informs that since 2000 (first year of the survey) overshoot has grown resulting in the change of the Earth Overshoot Day from early October to August. By August 2nd 2017[2], the humanity had already used up nature's entire budget for the year and went into ecological

[1] Global Footprint Network is an international research organisation that is measuring how the world manages its natural resources and responds to climate change. Every two years, Global Footprint Network, WWF, and the Zoological Society of London publish the Living Planet Report, a science-based analysis on the health of our planet and the impact of human activity.
[2] https://www.footprintnetwork.org/our-work/earth-overshoot-day/)

overshoot. For many industries, the environmental issue is a barrier to business, particularly the fossil industry. The delay in taking action to mitigate climate change is due to the conflict of information and disinformation among scientists and lobbies, although the Intergovernmental Panel on Climate Change (IPCC) has announced that the human influence on the climate system is unequivocal. IPCC have also proclaimed with 95% certainty that despite the radical changes, the next century will see an increase in temperatures (IPCC, 2015). Besides, a mathematical analysis of citation networks found that consensus on climate documents was formed in the early 1990s (Shwed and Bearman, 2010).

Technology is often referred to as the possible solution to the environmental crisis. According to Veiga and Issberner (2012, p. 128), 'innovations, particularly technological ones, are part of the solution. But they have been part of the ecological problem'. The blind belief in technology led authors as Tanuro (2014) to argue that "environmental" policies are far from addressing the essential issue: how to reduce material output and provide a decent standard of living to human beings. For him, current policies aim to prolong business as usual by avoiding any structural transformation that might question the power structure and values that lead to catastrophe. Huesemann and Huesemann (2011) provide insightful arguments, questioning the issue in their book *Why technology won't Save us or the Environment*. This idea refers to economist Joan Robinson (1964) when saying that 'it is far easier to build machines than to reorganise society' (Robinson, 1964, p.77).

However, even believing that technology alone is not enough to solve the current environmental problems, it is certain that it can collaborate to mitigate climate change and to adaptation to changes in the environment. In this context, eco-innovations are gaining increasing attention in literature as well as in government and business context (Hojnik and Ruzzier, 2016). By bringing environmental aspects into discussions, eco-innovations can affect and transform the innovation system in order to create sustainable processes (Carrillo-Hermosilla et al., 2010).

Like traditional innovations, eco-innovations may occur through different ways by combining materials and production processes, creating new products or offering a new attribute to an existing product in a new production method. They can also be related to the discovery of new supply of raw materials, to the opening of new markets and market niches, to a change in the composition of a product, to the extension of the lifetime of a product and so on. However, the main challenge towards the transition to a more sustainable, cleaner and more equitable society is to set innovation in a new context, as until very recently it only considered the economic and technical variables. This change means to value the social and environmental dimension of the innovation (Bleischwitz et al., 2009).

In addition to eco-innovation, new technological and methodological approaches are spreading in the industrial environment, offering promising perspectives. Life Cycle Assessment (LCA) is considered a valuable tool in the environmental sustainability of industry. It intends to revise the complex interaction between environmental aspects and the product life cycle, taking into account the entire product supply chain. According to experts, this tool makes possible an analysis of how the product may affect the environment during the phases of resource consumption, manufacturing processes, use and discard (Benedetto and Klemes, 2009; Piekarski et al., 2013; Welz et al., 2011).

In this context, the present study addresses LCA and its relationship with the generation of eco-innovations. It aims at reviewing and discussing the concepts of eco-innovation and LCA, as well as how the positive feedback mechanisms can help to reduce natural resources use and the generation of environmental impacts. In addition, the study makes a search on publications in reputed journals, aiming to identify the presence of eco-innovation and LCA themes discussed in the same documents. The results of an illustrative case on the relationship between LCA and eco-innovation are also discussed in the present study. With this background, we hope to contribute to a better understanding of the relationship between LCA and eco-innovations and to the possible convergence of these themes.

The paper is structured as follows. Section 2 presents a theoretical background for the paper, reviewing eco-innovation and LCA concepts. Section 3 presents the methodological approach and data. Section 4 discusses the results and findings. Concluding remarks are presented in Section 5.

2. Theoretical background

The current ecological crisis requires an understanding that there are ecological limits for human interventions on the planet. This will require crucial transitions in the current societal systems of production and consumption, as they are the root cause of environmental pressures. Such transitions will demand deep and far-reaching changes in prevailing paradigms, routines, technologies, behaviour and way of thinking (Boons 2009; EEA, 2015; Machiba 2010). In this context, firms play a crucial role as the largest consumers of natural resources and the main agents to cause environmental degradation (Cohen and Winn, 2007). Products and services also directly affect people’s lives, their behaviours and patterns of consumption (Agarwall, 2004; Gunther and Thorson, 1992). For these reasons, firms have been under great pressure to have an active position in addressing aspects related to energy and water use, reduction of emissions, adoption of clean technologies, management of natural resources and waste (Freeman et al., 2010; Montalvo, 2008; Zollo et al., 2013).

These and other climate change and environmental related challenges have raised an expectation that innovations would be the solution or the means to build the solutions to ecological problems (Boons et al., 2013; European Commission, 2010; OECD, 2011; Porter and Kramer, 2011). However, for a long time, the development and adoption of innovations – be it in products, processes, and forms of management or service offering – have been oriented by competiveness not by environmental concerns (Prado and Issberner, 2016; Veiga and Issberner, 2012). For the organisations, innovation is considered crucial for generating returns, reducing production costs and improving the quality and performance of products or services (Srinivasan et al., 2009; Teece, 1993). However, it is not unusual that the development and / or adoptions of environmental related innovations by organisations are associated to regulatory pressures. Regulations are identified as the main driver for different types of innovations (such as product, process, organisational) and influence both stages of the development and the diffusion of eco-innovations (Bossle et al., 2016; Hojnik and Ruzzier, 2016). Under these contradictory circumstances – being part of the problem, but also likely to be part of the solution – the role played by innovation is being questioned. This issue has received considerable attention from scholars, managers and policy-makers in an attempt to find out how innovations can help the transition towards a more sustainable model (Adams et al., 2016; Boons et al., 2013). For many of them, eco-innovations and LCA play a key role in this context (Bocken et al., 2012; del Río et al. 2016; Pacheco et al. 2017; Piekarski et al., 2013).

2.1. Discussing the concept of Eco-innovation

Within the literature that relates environmental concerns to innovation, there is a variety of conceptualisations for eco-innovation and related terms (Adams et al., 2016) which sometimes are used interchangeably (see Díaz-García et al., 2015; Karakaya et al., 2014; Xavier et al., 2017). In fact, in an earlier exploratory literature review, Schiederig et al. (2012) had already identified that the three different notions of green, eco/ecological and environmental innovation are largely used as synonyms while the concept of sustainable innovation included a social dimension which is not addressed by the previous notions (see also Boons et al., 2013; Hojnik and Ruzzier, 2016). OECD (2009) defines eco-innovation emphasising that it involves ‘broader social arrangements’ which can prompt changes in existing institutional structures. Despite that, studies on environmental management, sustainability and innovation seems to have paid little attention to innovation as a potential means to add social and environmental value to economic returns (Doherty et al., 2014). In a context of discussing innovation as a means for sustainable development, change is crucial – and changing the way things are done is directly related to core aspects of innovation. However, social aspects may be changed even if the motivation for the adoption of an eco-innovation is considered 'just' environmental or even only aimed at costs reduction. While in a period of transition towards a more sustainable model, measures such as performance and competitiveness may still be needed. Thus, for the purposes of this paper, we will focus on the definitions and usage of the concept of 'eco-innovation' as a starting point to address change – both incremental and radical (Carrillo-Hermosilla et al., 2010).

A growing body of literature on eco-innovation has been published particularly after 2009-2010 (Bossle et al., 2016; Díaz-García et al., 2015; Karakaya et al., 2014; Xavier et al., 2017), including literature reviews in recent years which provide an overview and a synthesis on eco-innovation and related issues (see Table 1). Some of them focus on eco-innovation drivers (see Bossle et al., 2016; Hojnik and Ruzzier, 2016; del Río et al., 2016) while others are even more context-specific focusing on determinants of eco-innovations in manufacturing SMEs (see Pacheco et al., 2017). Despite some variance in focus, databases and number of documents analysed, these reviews agree that eco-innovation is a topic of growing interest in the last decade whose definitions can greatly differ. This interest comes from both industry and academia with a particular interest on what makes a firm develop or adopt an eco-innovation – though regulations have shown to be the main motivation so far.

Table 1

Recent literature reviews on eco-innovation

Reference	Journal of publication	Focus of the review	Main Findings of the review
Díaz-García et al. (2015)	Innovation Management, Policy & Practice	General overview on eco-innovations	Increase in the relevance of this issue within academia since 2007; The use of this term should imply a full life cycle analysis of input and output factors; Six categories of recurring themes were identified (performance, drivers, process, context, types, and policy). In all of them, "drivers" is the main topic of research; At the macro level: literature highlights the relative importance of regional factors such as "transition regions" and "industrial

			districts"; At the meso level: market dynamics, pressure groups and networks are key elements in fostering eco-innovations; At the micro level: visionary management and managerial concern are considered two of the most important factors in the development of eco-innovations, along with key resources and capabilities (such as qualified personnel, networking and absorptive capacity and green organisational identity).
Bossle et al. (2016)	Journal of Cleaner Production	Drivers for adoption of eco-innovations	Growing interest in this concept, from both managerial and academic perspective; To boost performance, companies need to improve the focus in eco-innovation as an explicit goal of their strategies; Regulation is the most cited factor along with normative pressures and the need for efficiency (cost saving, for example); Although companies are starting to develop eco-innovations, motivation is still very much oriented towards compliance with standards and not to truly achieving sustainable goals.
del Río et al. (2016)	Journal of Cleaner Production	econometric analyses of firm-level drivers for adoptions of eco-innovations	The following issues are identified as gaps in the literature as they were missing or scarce in the studies analysed: An integrated theoretical framework which merges the insights from different approaches; The influence of some variables such as demand-pull and cost-savings, and internal and international factors; Studies on the drivers of eco-innovation versus drivers of general innovation; Analyses of the relevance of different drivers of eco-innovation for distinct eco-innovator and eco-innovation; Studies on middle income and developing countries; The use of panel data in the econometric analyses (most studies have relied on micro econometric methods based on cross-section data - mostly logit and probit models); Detailed econometric analyses on the distinct drivers and barriers to eco-innovation in different sectors and regions;

			The position of the firm in the value chain and the market structure and its influence on the propensity to eco-innovate.
Hojnik and Huzzier (2016)	Environmental Innovation and Societal Transitions	Drivers of eco-innovation	Regulations and market pull factors are the most critical drivers of eco-innovation in companies; Regulations remain a dominating driving force compared to other factors for different eco-innovation types (product, process and organisational eco-innovation, environmental technology and, environmental R&D); Regulations play a role in both stages of eco-innovation (development and diffusion) and prevail over economic incentive instruments; Product eco-innovation, process eco-innovation, organisational eco-innovation, and environmental R&D investments seem to be driven by common drivers, such as regulations, market pull factors, EMS, and cost savings, as well as to be positively associated with company size. Most studies focus on the adoption/diffusion stage.
Pacheco et al. (2017)	Journal of Cleaner Production	Determinants of eco-innovations in manufacturing SMEs	Twenty-three determinants of eco-innovations for manufacturing SMEs are identified and classified in seven categories (External context, Internal context, Strategies, Learning, Structure, Operations, and Results). The determinants considered most critical were: Governmental policy supporting eco-innovation; Availability of resources (people, technology, knowledge); Perception of the strategic relevance of eco-innovation; Technological advisory oriented to environment; Product and process eco-innovation oriented methods; Cooperation and partnership within supply networks. Some strategic alternatives to mitigate the impact of certain determinants are identified as deserving further attention: (i) the adoption of a proactive behaviour to co-create value developing eco-innovations in partnership with customers, (ii) the application of the PSS perspective on eco-innovation (Ceschin, 2013; Bertoni et al., 2015), (iii) the use for eco-innovation of specific tools consolidated in previous studies such as LCA, TRIZ, Eco-design, Biomimetic (Chen, 2014; Fresner et al., 2010; Recchioni et al., 2007),

			(iv) the establishment of partnerships within the supply chain oriented to eco-innovation, (v) the establishment of a culture favourable for eco-innovation.
Xavier et al. (2017)	Journal of Cleaner Production	Focus on eco-innovation models	The models analysed reveal a predominance of generic and descriptive characteristics; There is a gap of eco-innovation models related to organisational structural factors (specific skills, environmental capacity, culture, leadership) and to social aspects of sustainability; Opportunities for normative models can be highlighted, such as methods, tools and models, which can be adapted to systems and industrial segments. Application opportunity of the non-experimental models in segments not yet studied, such as: information technology, biotechnology, mechatronics, food, pharmaceutical, automotive, construction, military, naval; Despite some research focus on product-service system, no model of eco-innovation was proposed specifically to a service industry. Some studies have had their studies applied to SMEs, but no model direct at small TBCs (technology-based companies).

Source: The Authors.

From a historical perspective, many studies recognise Fussler and James (1996) as the first scholars to use the term in the specialised literature (Díaz-García et al., 2015; Karakaya et al., 2014; Pacheco et al., 2017). In their book *Driving Eco-Innovation,* the authors define eco-innovations as “new products and processes which provide customer and business value but significantly decrease environmental impact”. Similarly, many definitions have been stated since then which differ from the definition of innovation in Schumpeterian terms[3] in relation to the reduction of environmental burdens. Rennings (2000) observes this difference in terms of content of change and direction. While general innovation is neutral and open in all directions, eco-innovation is ‘motivated by concern about direction and content of progress’ (Rennings, 2000, p. 322). Oltra (2008) argues that the main specificity of any environmental innovation – beside a “positive impact” on the environment – is related to the determining role of regulation. Rennings (2000) and Oltra (2008) relate this specificity to the “double externality

[3] Schumpeter, J. A. (1934, 1980). The theory of economic development. Oxford University Press: London.

problem", which reduces the incentives for firms to invest in eco-innovations demanding the use of policy instruments and the existence of what Rennings (2000) calls the "regulatory push-pull" effect.

Other studies followed adding new perspectives to the reduction of environmental impacts. Some definitions, for example, brought an economic dimension from the industrial dynamics perspective. Along these lines, Andersen (2008) and Foxon and Andersen (2009) classify as eco-innovation any innovation that can attract 'green rents' in the market, reduce the net environmental impacts and create value for organisations. Ekins (2010) considered eco-innovation as any change that benefits the environment while increasing the economic and environmental performance of an organisation. Other studies bring the matter of motivation to the debate. For some, following OECD's definition, the concept of eco-innovation is not restricted to the intentionality of environmental improvement (OECD, 2009). In general, this is the perspective adopted by those studies, which analyse the drivers and determinants for the adoption of eco-innovations (Bossle et al. 2016; del Río et al. 2016; Hojnik and Ruzzier 2016; Pacheco et al. 2017). In many cases, there is evidence that the motivation for adopting an eco-innovation is not necessarily environmental, but rather, it is 'good for business' and brings environmental benefits as a positive side effect (EIO 2016; Motta et al., 2017; Oltra, 2008). As noticed by Carrillo-Hermosilla et al. (2010), environmental and other motivations may become entangled and thus challenging to establish a clear relationship that influences performance; at the same time, from a social perspective, the reasons to eco-innovate may not be so meaningful if the results of the implementation are positive.

From a more comprehensive perspective, Kemp and Pearson (2008) introduce the importance of the life cycle in the debate and define eco-innovations as:

> "the production, assimilation or exploitation of a product, production process, service or management or business method that is new to the organization (developing or adopting it) and which results, throughout its life cycle, in reductions in environmental risks, pollution and other negative impacts of resources use (including energy use) compared to relevant alternatives" (Kemp and Pearson, 2008, p. 7).

This definition highlights that besides a satisfactory environmental performance, it is also necessary that the product life cycle and the supply chain are analysed (Díaz-García et al., 2015; Jansson, 2011). Otherwise, a production chain may invalidate the environmental benefits of using products and services which are considered sustainable (Kemp and Pearson, 2008;

Kemp, 2009; O'Hare et al., 2010). Another important aspect of this definition is the comparison to other existent alternatives. As discussed by Oltra (2008), eco-innovations cannot be defined in terms of absolute environmental impact without referring to alternative technologies. Otherwise, rebound effects may be an undesirable consequence as many cost-saving innovations lead to increased expenditure.

The concept of eco-innovation has been evolving and currently includes any innovation that minimises the use of natural resources and reduces or recovers the discharge of harmful substances to the environment throughout the life cycle (EIO, 2016). This approach takes the usual focus from the end of life and brings it to the whole life cycle, creating opportunities for new business models and concepts such as sharing, leasing and remanufacturing (EIO 2016; Motta et al., 2017). As summarised in Table 2, common features in the definitions of eco-innovations found in the available literature include: novelty; reduction of environment burdens, use of natural resources, release of toxic substances; and a life cycle perspective. In this paper, we underline that eco-innovations are not just characterised by the reduction of environmental impacts but also by the removal or recovery of the consequences of these impacts. There are some impacts of climate change, for instance, that cannot be reverted – such as sea-level rise, changing geography and ocean acidification (IPCC, 2015). Nevertheless, it is possible to develop technologies to cope with the consequences of these impacts and to improve society's ability to adapt to these inevitable changes.

A transition towards sustainable development will require great efforts to change the usual patterns of production and consumption that has made society get used to waste and over-consume natural resources at least since the beginning of the twentieth century. Nevertheless, there are viable eco-innovations being implemented in different fields and sectors that highlight new opportunities being introduced by the industry and analysed by academic research. These include plastics, bio-based products, food waste, critical raw materials, construction and demolition, among others (EIO, 2016). There are promising eco-innovations with the potential to be scaled-up though most part is concentrated in market niches (EIO, 2016). This means there is an urgent need for the dissemination of these eco-innovations and eco-innovative strategies, so they can reach the mainstream. We suggest an approach that considers the whole life cycle in association of LCA and eco-innovation as an indispensable component of sustainable development research.

Table 2

Definitions of eco-innovation.

Relevant aspects of the definition	**Definition of eco-innovation(s)**	**Reference**
Novelty; Reduction of environment burdens.	"the process of developing new products, processes or services which provide customer and business value but significantly decrease environmental impact"	Fussler and James (1996)
Novelty (even if it is not novel to the market or to other firms) Reduction of environment burdens.	"all measures of relevant actors (firms, politicians, unions, associations, churches, private households) which develop new ideas, behaviour, products and processes, apply or introduce them and which contribute to a reduction of environmental burdens or to ecologically specified sustainability targets"	Klemmer et al. (1999)
Reduction and repairing of environment burdens.	"Innovation which serves to prevent or reduce anthropogenic burdens on the environment, clean up damage already caused or diagnose and monitor environmental problems."	Hemmelskamp (2000)
Novelty; Social perspective; Reduction of use of natural resources; Reduction of release of toxic substances; Life cycle perspective.	"the creation of novel and competitively priced goods, processes, systems, services, and procedures designed to satisfy human needs and provide a better quality of life for all, with a life cycle minimal use of natural resources (materials including energy, and surface area) per unit output, and a minimal release of toxic substances"	Europe INNOVA (2006)
Novelty (even if it is not novel to the market or to other firms); Reduction of environment burdens; Life cycle perspective.	"the production, assimilation or exploitation of a product, production process, service or management or business method that is novel to the organisation (developing or adopting it) and which results, throughout its life cycle, in a reduction of environmental risk, pollution and other negative impacts of resources use (including energy use) compared to relevant alternatives"	Kemp and Pearson (2008)
Novelty (even if it is not novel to the market or to other firms) Reduction of environment burdens; Life cycle perspective	"the production, assimilation or exploitation of a novelty in products, production processes, services or in management and business methods, which aims, throughout its life cycle, to prevent or substantially reduce environmental risk, pollution and other negative impacts of resource use (including energy)"	European Commission (2008)
Reduction of environment burdens;	"the same as other types of innovation but with two important distinctions: 1) eco-innovation represents	OECD (2009)

Intended or unintended motivation; Social perspective.	innovation that results in a reduction of environmental impact, whether such an effect is intended or not; 2) The scope of eco-innovation may go beyond the conventional organisational boundaries of the innovating organisation and involve broader social arrangements that trigger changes in existing socio-cultural norms and institutional structures"	
Novelty; Environmental sustainability.	"Innovations that consists of new or modified processes, practices, systems and products which benefit the environment and so contribute to environmental sustainability"	Oltra and Saint Jean (2009)
Environmental performance; Intended or unintended motivation; Reduction of environment burdens.	"an innovation that improves environmental performance (Carrillo-Hermosilla et al., 2009), in line with the idea that the reduction in environmental impacts (whether intentional or not) is the main distinguishing feature of eco-innovation."	Carrillo-Hermosilla et al. (2010)
Novelty; Reduction of use of natural resources; Reduction of release of toxic substances; Life cycle perspective.	"The introduction of any new or significantly improved product (good or service), process, organisational change or marketing solution that reduces the use of natural resources (including materials, energy, water and land) and decreases the release of harmful substances across the whole life cycle"	EIO (2011)

Source: The authors.

2.2 Reviewing Life Cycle Assessment

The life cycle assessment (LCA) has emerged as a methodological tool that evaluates the impact and environmental aspects of a product, process or service throughout the different stages of its life cycle, allowing complete or partial analysis of these stages. All different activities – such as materials, supply chain, distribution, use and final destination – may be analysed to quantify the use of natural resources, emissions, environmental and health impacts that might be associated (Piekarski et al., 2013; Welz et al., 2011). LCA methodology is internationally standardised by the *International Organization for Standardization* (ISO) through the ISO 14040 series (ISO, 2001; ISO, 2006), which are regarded as the most relevant standards for environmental assessment based on product life cycle (Klöpffer, 2012).

Due to its more comprehensive perspective, LCA can support the Environmental Management System (EMS) and interfere in the design, development and manufacture of the product. It offers the possibility of a quantitative analysis to identify opportunities for environmental improvements in products, processes and services, enhancing decision-making processes in organisations (Bocken et al., 2012; Piekarski et al., 2013, Motta et al., 2015a,b). The use of LCA and its importance are highlighted at UNEP (2011) as the methodology used to identify the environmental impacts of production processes performed by various industries around the world. Such impacts may result from any part of the product life cycle: in the phase of extraction, production / manufacture, consumption / use or post-consumption. As suggested by Guinée et al. (2001), there are several benefits in using LCA methodology for the development of innovation, decision support, comparison with competitors, promotion of new products, and analysis of problems.

2.2.1 Use promotion

Regulatory and market pressures contribute to the diffusion of LCA. They force organisations to learn more about the environmental impacts and to improve their environmental strategy (Berkhout, 1996). As a result, some organisations, for example, have created an environmental management department that gets in charge of promoting the learning and structuring the actions around the issue. The use of LCA as a generator of relevant environmental information to the decision makers became more evident in the last decades. Life cycle thinking has become a crucial guideline, which takes into account not only the impacts generated and the resources consumed in one particular organisation, but rather considers the environmental consequences throughout the product cycle (Borghi et al., 2007; Liamsanguan and Gheewala, 2008; Löfgren et al., 2011; Piekarski et al., 2013; Pieragostini et al., 2012).

LCA, mainly through its inventory, analyses in detail the environmental impacts of the life cycle activities and classifies them in terms of Life Cycle Impact Assessment, which is the estimation and calculation of potential impacts on the environment. It presents the phases of the product life cycle that have higher environmental impact (Cambria and Pierangeli, 2012). Based on this analysis, it is possible to generate valuable information for decision-makers to interpret and promote the necessary and appropriate changes.

2.2.2 LCA and innovations

There is a strong relationship between technological innovation and environmental management to sustainability achievement. The technological innovation process may promote considerable changes in the production process, in labour relations and in society itself. In this sense, the diffusion of environmentally sound technological innovation can be used to take the place of unsustainable production and consumption means, building a new paradigm and new technological guidelines. Today, clean technologies are seen as viable alternatives to the current structure of production and consumption, which is threatening the quality of life on the planet (Global Environmental Change Programe, 2001; OECD, 2012).

According to Berkout (1996), in the past it was sufficient for organisations to be concerned with the emission limits and product standards. In the present, the achievement of environmental objectives managed by organisations reaches new and broader horizons and includes the entire life cycle of the products, which in most cases are out of direct control. As previously mentioned, the life cycle approach has shown to be an appropriate and comprehensive tool to support decision-making processes related to environmental issues in business. It is able to direct efforts, which contribute to the generation of technologies that add to the capacity of mitigating the environmental degradation and adapting to unavoidable changes. The resulting knowledge enables the recognition of vulnerabilities and the search for new options to improve the environmental performance of processes and products analysed (Berkhout, 1996).

LCA adoption can provide basic technological changes and generate innovations that should transform organisations and their market, creating value opportunities (Guinée et al., 2001; Özdemirci, 2011; Piekarski et al., 2013). O´Hare et al. (2010) point out that the product life cycle approach is considered a crucial aspect for two main reasons. First, if only part of the life cycle is considered, more significant problems in other areas of the life cycle may be missed. Secondly, solutions that are effective for one life cycle phase may create new environmental impacts in other life cycle phase. Therefore, LCA can reduce or even eliminate the risk that a decision aiming at reducing pollution simply shifts the environmental problem from one phase to another or from one environmental impact category to another.

2.2.3 LCA phases

LCA methodology is organised in four stages or phases: (i) defining scope and objectives of the study; (ii) analysis of inventory; (iii) environmental impact assessment; and (iv) interpretation of results. The first phase demands special attention as it defines how the whole process and other phases will be carried out. During the first phase, the purpose of the analysis, the system boundaries, the functional unit and assumptions will be defined (Piekarski et al., 2013). Benedetto and Klemes (2009) reminds that the aims and scope defined should be rectified or calibrated in an iterative process. The second phase refers to the Life Cycle

Inventory (LCI) when data is collected to identify and quantify materials and energy inputs, wastes and emissions (Benedetto and Klemes, 2009). The third phase will assess the environmental impacts quantified in the previous phase through classification, characterisation, normalisation and valuation (Piekarski et al., 2013) and set impact categories (Benedetto and Klemes, 2009). The fourth and last stage will interpret the information derived from second and third phases, analysis of inventory and environmental impact assessment to draw conclusions to support decision making (Benedetto and Klemes, 2009; Piekarski et al., 2013). This stage can be crucial to identify opportunities for the implementation of eco-innovations.

3. Methods and data

This theoretical manuscript aims at investigating the relationship between LCA and the generation of eco-innovations. Drawing on contributions from literature on eco-innovation and LCA, the paper analyses available evidence on this relationship in a context of the transition towards sustainable development. To structure the debate, we offer a conceptual approach (see section 2) and an illustrative case on international researchers' and practitioners' perceptions on the potentially positive relationship between eco-innovation and LCA.

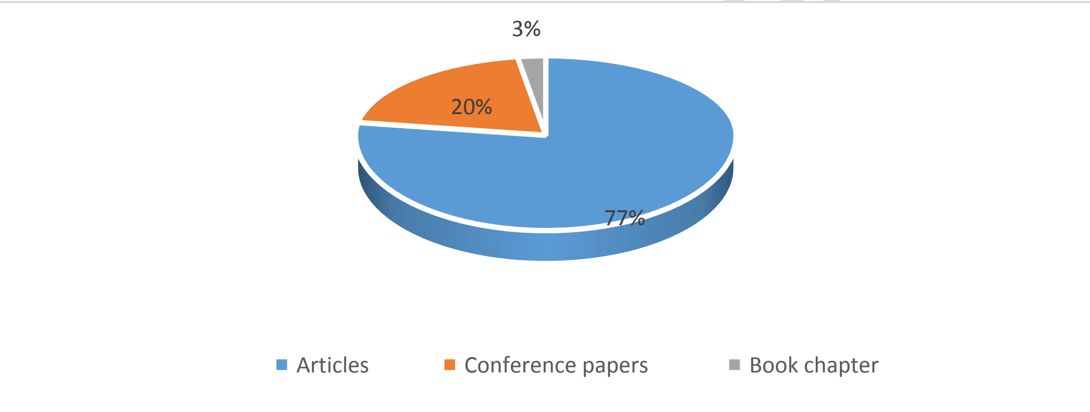
3.1 Search in the databases

To address the issue proposed, the study started by gathering data in the Web of Science (WoS) Core Collection and in Scopus. WoS is a database of references with abstracts that indexes only the most cited journals in each area of knowledge. It offers more than 9,000 journals and 5 collections – the oldest since 1945. Scopus is a database of references with abstracts, which offers more than 21,000 journals from 5,000 international editors, since 1823. These two databases are recognised as having long-term worldwide coverage and the largest number of peer-reviewed journals; they have a considerable match between the results (Gavel and Iselid, 2008) and usually work best when both are combined for the search (Chappin and Ligtvoet, 2014).

Once the databases were selected, we defined the keywords for the search. Although there is a close relationship to other similar concepts (see Section 2.1), we used the descriptors "eco-innovation" and "LCA" as we intended to focus on the specific use of eco-innovation. A keyword Boolean search with the descriptors were used to search in the topic, title, keywords and abstracts. The period of search considered all years in both databases. The final corpus covers a time span between 2003 and 2017. The data was collected in November 2017. This search identified 28 documents in WoS and 37 documents in Scopus, in a total number of 65 documents. In WoS, among the 28 documents identified in the search, 23 were articles, 4 were conference papers, and 1 was a review. In Scopus, among the 37 documents identified in the search, 25 were articles, 1 was an article in press, 10 were conference papers, and 1 was a book chapter. After reading the abstracts, and when necessary the document itself, some documents had to be excluded for the following reasons: (i) the document was repeated in the results of both databases; (ii) the document did not directly discuss eco-innovation and LCA, but peripherally cited one of the terms; (iii) the document presented incomplete data for analysis. After the exclusions there were 35 documents left: 27 articles (77.14%), 7 conference papers (20%) and 1 book chapter (2.86%) as represented in Figure 1. The journals where the articles were published and the conferences where the papers were presented are summarised in Table 3.

Figure 1

Documents on eco-innovation and LCA – Web of Science and Scopus.



Source: The authors.

Table 3

Place and area of publication – documents on eco-innovation and LCA between 2003 and 2017.

Journal / Conference	Area	Number of documents
Journal of Cleaner Production	Cleaner Production, Environment, and Sustainability	8
International Journal of Life Cycle Assessment	Life Cycle Assessment	3
Procedia Engineering	Engineering	2
Energy and Buildings	Energy and Building Science	1
Smart Innovation, Systems and Technologies	Computer Science	1
International Journal on Interactive Design and Manufacturing	Design and Manufacturing	1

Sustainability (Switzerland)	Sustainability	1
International Journal of Production Economics	Engineering management	1
DYNA (Colombia)	Engineering and Technological Sciences	1
Frontiers of Mechanical Engineering	Mechanical Engineering	1
Science of the Total Environment	Environment	1
Expert Systems with Applications	Intelligent systems	1
Technovation	Technological innovation	1
Building and Environment	Building Science and Environment	1
Ecological Economics	Ecology and Economics	1
Journal of Environmental Management	Management and Environment	1
Bio-based and Applied Economics	Agriculture and Applied Economics	1
22nd International Conference on Production Research, ICPR 2013	Production Research	2
Conference on Transport Research, Athens, Greece 2012	Social and Behavioural Sciences	1
2010 IEEE Green Technologies	Green Technologies	1
Electronics Goes Green 2012+, ECG 2012 - Joint International Conference and Exhibition 2012	Electronics	1
Summer School Francesco Turco 2013	Industrial Engineering and Operation Management	1
International Conference on Engineering Design, ICED 2017	Engineering	1

Source: The authors.

3.2 Illustrative case: testimony of market experts

To add to the debate on the potentially positive relationship between LCA and eco-innovation, we present an illustrative case on international researchers' and practitioners' perceptions on this relationship.

3.2.1 Data collection

Data collection aimed at identifying the following aspects (among others): the state of the art of the LCA; the maturity level of LCA in developed countries or regions, such as Switzerland, Netherlands, Nordic countries, Germany, Japan and North America; different actors involved and their forms of interaction; the relationship between LCA and eco-innovative practices[4]. For

[4] The data used in this paper is part of the Ph.D. thesis of the first author.

this purpose, we designed a survey which was publicised and submitted through the *LC Net – November-December 2015 Edition*, the newsletter of the *Life Cycle Initiative*. We used SurveyMonkey – an online survey development cloud-based software, which provides customisable surveys – for the data collection via web. The survey consisted of 15 questions organised in 9 categories according to the aspects being investigated. For the purposes of this paper, though, we will discuss only the data related to the relationship between LCA and eco-innovation. The questions covering this topic were structured as open questions and are reproduced below:

> ***Can you notice any relationship between LCA and innovation?***
>
> ***Can you give an example of an innovation that could be generated or that has been generated from an LCA study?***

3.2.2 Sample

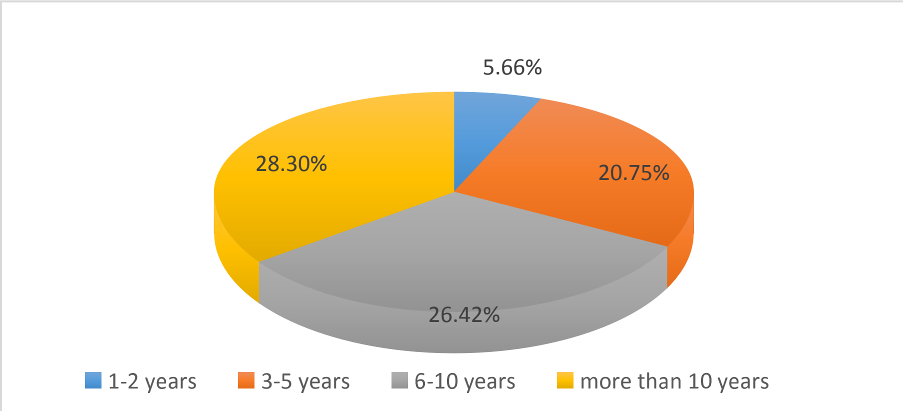
The *Life Cycle Initiative* was chosen to be the channel to access international researchers and practitioners with experience on LCA as it is regarded as a worldwide influential organisation on the issues concerning LCA practices and its dissemination. The *Life Cycle Initiative* is a public-private, multi-stakeholder partnership hosted by UN Environment with the aim of 'enabling the global use of credible life cycle knowledge by private and public decision makers'[5]. Among their members, they include governments (18 representative bodies), 30 businesses, 32 scientific and civil society organizations, 161 individuals and 17 sponsors.

At the time of the data collection, November-December 2015, the *Life Cycle Initiative* had 106 individuals among their members, who received the survey via the newsletter. Among these 106 individuals, 86 effectively replied and submitted the survey back, with an answer rate of approximately 81%. The survey addressed the respondents' profile in two aspects: work experience – in years; and country where industry or research activities on LCA were performed. Most of the respondents are experienced on LCA aspects, as 54.72% of them have been conducting activities in the area for at least six years (see Figure 2 with four year ranges of work experience).

[5] http://www.lifecycleinitiative.org/about/about-lci/ Access on October 30th, 2017.

Figure 2

Survey respondent profile – work experience.

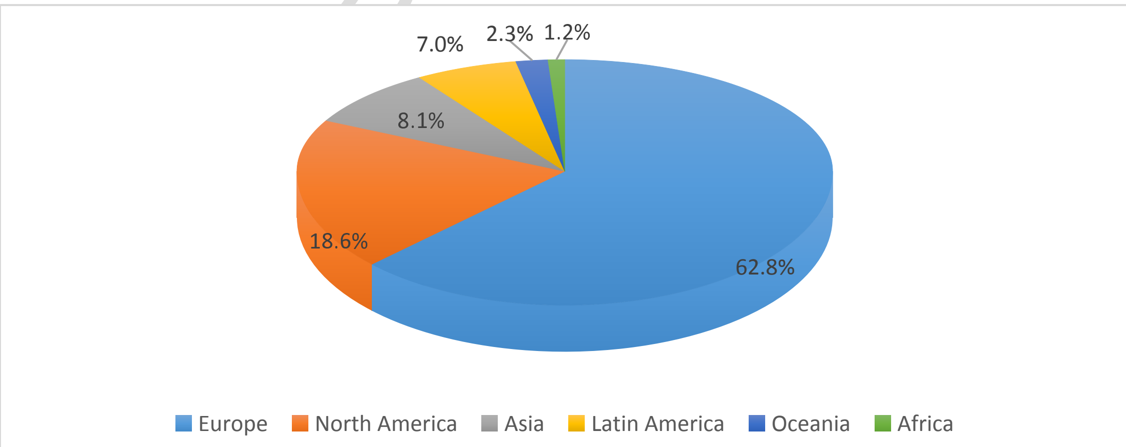


Source: The authors.

In terms of where the industry or research activities on LCA were being performed, the respondents informed 33 different countries. The countries with the highest number of members were United States of America (USA), France, Switzerland, Italy, Germany, Canada, Spain and the Netherlands. The respondents informed that they were conducting their activities as follows: 54 in Europe (62.8%); 16 in North America (18.6%); 7 in Asia (8.1%); 6 in Latin America (7.0%); 2 in Oceania (2.3%); and 1 in Africa (1.2%). The distribution among continents is presented in Figure 3.

Figure 3

Survey respondent profile – continents of activity.



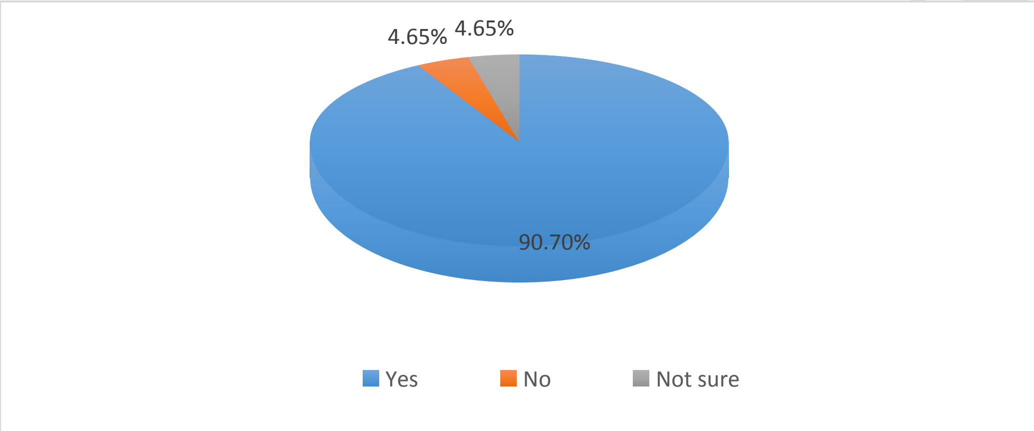
Source: The Authors

3.2.3 Survey responses

Among the final sample of 86 responses to the survey, an expressive majority of 78 respondents (90.7%) can notice a direct relationship between LCA and innovations. The other 8 respondents do not notice this relationship or are not sure about it. The respondents' perception – when responding to the question 'Can you notice any relationship between LCA and innovation?' – is represented in Figure 4.

Figure 4

Survey responses to the question – 'Can you notice any relationship between LCA and innovation?'.



Source: The authors.

For the question, 'Can you give an example of an innovation that could be generated or that has been generated from an LCA study?' just 6 respondents gave detailed information containing examples of innovations that had been generated from an LCA study. These responses are reproduced and organised in Table 4 below.

Table 4

Examples of innovations generated from an LCA study.

Organisation	Action	Results
Marks & Spencer	The carbon footprint was calculated considering the entire life cycle of the products (underwear sector), considering the phases from the manufacturing of components to transportation and even the energy expenditure of customers when using, washing and drying their underwear.	The innovative features of renewable energy and waste reduction initiatives implemented at this site have helped reduce the energy intensity of the energy used by 33% compared to traditional production.

Dyson Airblade	The company was certified by Carbon Trust, analysing the life cycle of its production, using LCA to evaluate a unique impact category, in this case the carbon footprint. The greatest impact on the carbon footprint of the product is related to the energy in its use, which represents 90.8% of the total carbon emissions. Although it accounts for less than 1% of total GHG emissions, the product disposal phase has also been studied and most parts of the product can be recycled.	The innovative product, made of ABS polycarbonate, a strong and flexible plastic used to make shields and police helmets, produces about 50% less CO2 emissions during production than the aluminium equivalent.
TaTa Motors	The Tata Motors Research, Engineering and Sustainability Center in Pune presented the hotspots in evaluating the life cycle of the Nano car, which was the first analysis made from cradle to grave of a vehicle made by the company itself.	It was a pioneering practice that brought environmental benefits to the vehicle.
BioBuilt (a European Union project for the construction industry)	The objective of the project is to use biocomposites to reduce the energy incorporated in the facade of buildings, support structures and internal partitions, by at least 50% compared to conventional materials without cost increase.	This will lead to a radical change in the use of sustainable low carbon building materials through the replacement of aluminium, steel, brick and concrete in buildings.
Tesla Powerwall	An LCA study was performed in the residential energy system.	The Tesla Powerwall home battery system consists of backup batteries that store the energy of the sun for use at night or to protect the home in a power failure.
Airline Company	An LCA study was performed and demonstrated that the weight of tableware had a pronounced impact on overall environmental impacts.	The replacement of the cutlery by plastic ones aboard airline flights, providing a significant reduction in environmental impacts.

Source: The authors.

4. Discussion

The analysis of the literature of eco-innovations and LCA brings promising results regarding the possibilities of convergence of these two fields of study. However, the analysis also reveals some difficulties for this convergence to progress. Some assumptions and suggestions will be discussed in the first part of this section. After that, from the elements examined in sections 3.1 and 3.2, elements that can collaborate to evaluate the challenges to converge LCA and eco-innovation will be discussed.

4.1 Can the LCA be instrumental to the emergence of eco-innovations?

Returning to the starting question of this paper, some points have to be better clarified, so that the results can be properly apprehended. First, the respondents of the survey provided a positive answer regarding the link between LCA and eco-innovation (90.7% of them responded positively, 4.65% of them were not sure about this relationship and 4.65% did not perceive this relationship). In addition, experts were invited to report examples of eco-innovations derived from the application of LCA and eco-innovation, which gave consistency and reliability to the answer to the first question. They provided six interesting examples of eco-innovations derived from LCA that may be useful in other case studies.

An investigation of the literature on eco-innovation and LCA can also be a valuable source of information on the relationship between these two topics providing different and complementary insights. The search on the subject conducted in the two databases Web of Science and Scopus revealed some interesting points for discussion. The survey dealing with both eco-innovation and LCA resulted in 35 documents, 27 articles, 7 conference papers and 1 book chapter. It is difficult to sustain whether it is a significant number or not, but considering that eco-innovations only started to appear as a research theme in 1990, it is possible that this literature is still in its early phase, and therefore tends to grow, as the tendencies shown in the literature reviews analysed.

What is remarkable in the results obtained with the search in the databases (table 3) was the almost absence of traditional journals in the innovation area; only *Technovation* appears in the results, with just one article. As for LCA, *Journal of Cleaner Production*, with 8 articles, leads the ranking, as might be expected, followed by *International Journal of Life Cycle Assessment*, 3 articles and *Procedia Engineering, 2 articles*.

This result, at first glance, suggests that the area of innovation is less concerned with the LCA as a source of innovations or is not familiar with this methodology. To obtain an adequate explanation, a new research would be needed. Being essentially studied in engineering and management, the result of the research, somehow, informs about the nature of the analyses carried out in the literature. In this category of journal, the eco-innovation should be approached much more for its technological than economic, social and even political characteristics. At first, this does not pose a problem for the convergence of these two areas, but suggests the existence of an inevitable bias in the approach adopted in these papers. Themes like eco-designs and equivalent terms (like sustainable design, and design for the environment) appears in 29 abstracts selected in the database search. In the context of LCA, eco-design is associated with the development of products with the aim of reducing negative environmental impacts.

Thus, why did not the area of innovation incorporate the LCA in its studies on eco-innovations? This and other questions arise from the results obtained in this research, for which there are no elements to answer yet; they will require new investigations designed specifically to provide a satisfactory answer. Returning to the central question in the introduction of this paper on the convergence of the LCA and eco-innovation, some clarifications can be made. It seems that convergence is progressing, but much more due to the incorporation of eco-innovation into LCA studies than the opposite. The persistence of this tendency can lead to an overemphasis on technological and methodological aspects, to the detriment of less objective aspects, such as ethical, social and political factors, of some approaches to eco-innovation.

4.2 What aspects should converge?

In theoretical terms, it will be difficult to assess whether there are more complementary features between LCA and eco-innovation, than discrepancies. Being two different fields of analysis, with their approaches aimed at different purposes, at first, the connection seems complicated. Nevertheless, it is important to emphasise that a convergence can be due both to the similarity of themes and to their complementarity. What is intended here is an exercise designed to identify and compare the characteristics of these two subjects. In doing so, some elements of the analysis may perhaps provide the basis for a better understanding of the convergence process between LCA and eco-innovation.

4.3 Mapping the main features

Some characteristics of eco-innovation and LCA are confronted in Table 5 to clarify the convergence analysis of these two subjects. The authors, based on current knowledge on the subject, proposed the six characteristics of LCA and eco-innovation. Table 5 shows points of similarities and discrepancies that possibly have implications for the convergence process. The **fields of studies** were referred previously in this paper. LCA and eco-innovation belong to different traditions of thought, with its idiosyncratic schemes of working. It means that the expected contributions will have distinct theoretical backgrounds, perspectives, aims, methods and so on. Nevertheless, both fields of studies are **committed** to sustainability through the technology development and application that minimise[6] the impacts of the humans' activities on the biosphere. The eco-innovation is concerned with the development of eco-efficient product and processes, while LCA aims to identify the consumption of natural resources in all stages of the LCA, in order to enhance the environmental performance of the whole production cycle. The **skills** of the typical professional in each area are diverse. Creativity, risk-taking, collaborative, knowledge gathering are typical professional skills in innovative firms. Concerning the LCA, the typical professional have to master methodologies and management tools, as well as to perform analytical tasks.

The **complexities** faced by each area are also divergent. The challenge to eco-innovate is to cope with market uncertainties and face competition. Gathering information is a key problem in the LCA process as there are usually information gaps in one or more stages of the LCA, sometimes compromising the results and hindering subsequent decision-making. In terms of information **sensitivity**, both areas are concerned, but for different reasons. Innovation in general is constrained by issues of business secrecy and appropriability in many business strategies in order to retain market advantage. Data sensitiveness also concerns the LCA, because the assessment of each stage of a product life cycle requires the collection of strategic and even confidential information of the organisation. Additionally, collecting physical data in all LCA stages is not always possible, which may lead to results that are not robust at all times due to the need to replace specific data with generic data in some cases. The **forms of collaboration** are also crucial for eco-innovations that normally face a trade-off between the openness and the possibility of enhancing the quality and timing of an innovation. The aggressive conduct of competitors and opportunistic behaviour of partners are also matters of concern. In the case of LCA, networks creation were the ideal means to exchange technical information since the earlier stages of its formation. Governed by method, standards and rules, much of its process can be shared since early times and are object of international cooperation agreements.

[6] In this paper, the authors preferred to use *to minimise or reduce environmental impacts* rather than *eliminating impacts* as they believe that any process of material transformation inevitably produce some ecological impact, however small.

Table 5

Key factors in the convergence between LCA and eco-innovation.

Key Factors	Eco-innovation	LCA
Field of study	Innovation, technical change	Management, industrial production
Commitment	Eco-efficiency, new products and processes	Assess environmental impacts associated with all stages of a product (service) life cycle, generates information for decision-making
Skills	Creative, risk taker, collaborative, knowledge gatherer	Methodical, analytical thinking, managerial
Sensitive area	Strategic knowledge, Innovation appropriability	Availability of reliable data during inventory phase, decisions on trade-offs
External environment interactions	Networks of firms, strategic partnership, secrecy shield	Networks of firms, international cooperation agreements

Source: The authors.

5. Concluding remarks

The present discussion intends to contribute to the debates about fighting the ecological crisis from changes in productive efficiency, even considering their limited scope of action. This paper starts addressing and discussing critical aspects of the ecological crisis and the need to find an appropriate way to deal with it. Regarding the crucial role of business in the environmental crisis, some ideas emerge as promising. The research conducted in the present paper show evidences of the existence of links between LCA and eco-innovation. Some elements of the recent literature on eco-innovation and LCA were brought into discussion. An illustrative case was presented showing that the LCA opens opportunities for organisations to eco-innovate. The relationship between LCA and eco-innovation was investigated in documents retrieved from databases containing prestigious journals. With the findings, we identified the low representativeness of the academic production incorporating the two themes in traditional journals of the area of innovation.

Generally speaking, we are optimistic about the possibilities of convergence of eco-innovation and LCA. However, it is quite plausible that with the predominance of studies linking both themes in engineering and management, there will be a bias in this convergence. One question to pose is 'why is there so little attention to the connections between LCA and eco-innovation in the literature on eco-innovation?' Another question is 'what will be the loss in environmental terms with this predominance?' To be properly answered, those questions will require further research. Nevertheless, one possibility of this imbalance in terms of interests in both areas may be the fact that the innovation studies are impregnated with economic concepts, where 'money' is a determining attribute; physical measures, such as the emission of greenhouse gases, are not typical units. In the Anthropocene times, more and more physical measures, such as the ecological footprint, gas emissions, among others, will gain prominence in decision making about innovation.

We hope that this work can motivate practical applications of eco-innovations arising from LCA methodology, leading to environmentally sustainable patterns of production and consumption. We also hope that future case studies on the topic could be developed. Finally, uncertainty remains about whether at some point it will be possible to link these two distinct theoretical bodies, eco-innovation and LCA, creating the foundations to a new research area.

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