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1. Abstract

This paper aims to examine the application of life cycle assessment (LCA) as it has appeared in studies of supply chain management (SCM) in order to explore the potential utility for practitioners. Despite its widespread application in environmental studies, research incorporating LCA into SCM has been very limited, though potential benefits for this match have been identified. This paper employs a systematic literature review to explore these two topics as they relate to one another. Results show that LCA and LCA-based concepts do appear in the literature, with important implications for managers in their pursuit to improve supply chain performance.

Este trabajo pretende examinar la aplicación de los análisis de los ciclos de vida (LCA) como ha aparecido en estudios de la gestión de las cadenas de suministro (SCM) para poder explorar la potencial utilidad para profesionales. A pesar de su extendida aplicación en los estudios del medio-ambiente, la investigación que incorpora LCA en SCM ha sido más limitada, aunque se ha identificado unos beneficios potenciales para su aplicación. Este trabajo emplea una revisión de la literatura sistémica para considerar los dos temas y como se relacionan entre ellos. Los resultados muestran que LCA y los conceptos basados en LCA aparecen en la literatura, con implicaciones para directores que intentan mejorar el desempeño de las cadenas de suministro.

2. *Keywords:* life cycle assessment, life cycle management, supply chain management, sustainability, life-cycle thinking

3. Introduction

The international community has shown increasing concern for the impact of human activity on the environment in the last several decades. An increasing population coupled with environmental factors such as decreasing resources and global climate change has led a multitude of groups, among them governments, international organizations, NGOs, and private enterprises, to focus on the mitigation of negative environmental effects and to strive for economic, environmental and social sustainability.

The topic of sustainability has figured prominently in the business context. Initially, initiatives focused on incorporating environmental issues, but there has been increasing focus on the importance of social aspects of sustainability as well (Ahi & Searcy, 2013). These three aspects of sustainability in the business context are referred to as the Triple Bottom Line. Researchers and practitioners have dedicated a great amount of effort to explore sustainability in this context (for a review, see Abbasi & Nilsson, 2012). However, much of the research which has been carried out focuses on firm-level units of analysis. While beneficial, several authors have highlighted the limitations of using firm-level indicators of sustainability. For example, Larson *et al.* (2012), in an attempt to analyze greenhouse gas (GHG) emissions in Norway, note that firms often are able to reduce their own emissions through practices which then increase them in other stages of the product life cycle. These authors observe that to reduce emissions (and the taxes that accompany them) a firm might choose to turn to a third party located in another country with less stringent regulations to produce a more environmentally harmful component at lower cost. For the firm, emissions decrease, yet the overall effect is a net increase. Thus, to truly understand the environmental effects of a particular product or service, a top-down approach that focuses on the entire product life cycle is essential.

Though extensive research has been carried out on measuring the environmental costs at the product level in the environmental sciences, research using this level of analysis in a business context has been profoundly limited. Here, a branch of operations management, supply chain management (SCM), which focuses on multiple firms, offers a potential avenue to incorporate the concepts offered by life cycle assessment (LCA), which considers product life cycles, into a business context. SCM has grown exponentially in popularity in the past decades as a means for firms to gain competitive advantage through reduced monetary risks and increased profits (Fawcett *et al.,* 2008). As Ashby *et al.* (2012) note, the multiple firm nature of SCM, in which cooperating firms often share information as well as performance measures, is a "step toward the development of sustainability".

Admittedly, sustainability is by no means a new topic in the study of supply chain management. Indeed, Ashby *et al.* (2012) reviewed 108 academic research papers dealing directly with sustainability and supply chain management, referred to as sustainable supply chain management (SSCM), showing that the two concepts have become highly intertwined in research. However, research on sustainability using the supply chain level as the unit of analysis (*i.e.*, multiple firms) is decidedly lacking (Miemczyk *et al.,* 2012). Given that firms may opt to shift their own environmental costs to other points on the supply chain, this is troubling. In this context, LCA or "cradle-to-grave" analysis presents a potentially fruitful tool for the evaluation of the supply chain, and yet, a recent literature review revealed only three articles dedicated to LCA in supply chain management literature (Ashby *et al.*, 2012). This is especially relevant given that emission requirements are likely to become more stringent as governments strive to meet international environmental objectives. Though LCA has been recognized as having inconsistencies in its measures, even of the same product type, its potential as a management tool could, among other things, help firms develop useful performance measurements at the supply chain level and address the “significant and persistent gap between the diffusion of sustainability discourse and its practical application” (Ashby *et al.*, 2012). Moreover, employing LCA or LCA-based “life-cycle” thinking offers a “currently untapped ability to inform managerial decision-making” (Subramanian *et al.*, 2008), not only to reduce environmental impacts, but also to obtain costs savings through initiatives such as remanufacturing.

This paper seeks to explore LCA from a SCM perspective to identify potential applications and limitations for practitioners. After an overview of SSCM and LCA, a systematic literature review is carried out to explore the linkages between LCA and SSCM as they exist in the academic literature. Finally, the conclusions, limitations and possible future directions of study are presented.

4. Revision of Key Concepts

Before examining the link between LCA and SCM in the literature it is important to explore the topics relevant to the subject. Here, three areas are essential: SSCM, LCA, and evolving concepts of LCA within a supply chain management context.

4.1 Sustainable Supply Chain Management

The concept of SCM has emerged from multiple disciplines in response to an increased need for companies to effectively coordinate with outside suppliers (Mentzer *et al.*, 2001). For the purposes of this paper, the supply chain refers to “set of three or more entities (organizations or individuals) directly involved in the upstream and downstream flows of products, services, finances, and/or information from a source to a customer” (Mentzer, 2001). While the definition of the supply chain is generally accepted within the field of operations management (Mentzer, 2001), difficulties exist with defining SCM, even as it continues to evolve in practice (Halldorsson *et al.*, 2007). Several prominent definitions are presented in Table 1. In general, the goals of SCM differ from that of logistics in that SCM extends beyond the traditional boundaries of the firm to include multiple organizations (La Londe & Masters, 1994). Also, Mentzer *et al.* (2001) distinguish between the philosophy of SCM, which they refer to as having supply chain orientation, and the actual management practices to achieve improved performance at the supply chain level. This implies that some firms may be more supply chain-oriented than others (Lengnick-Hall *et al.*, 2013).

Table 1: Objective of Supply Chain Management

Authors	Year	Objective
Chen & Paulraj	2004	"Supply chain management seeks improved performance through better use of internal and external capabilities in order to create a seamlessly coordinated supply chain, thus elevating inter-company competition to inter-supply chain competition"
Fisher *et al.*	2010	"The purpose of supply chain management is to improve the long-term performance of individual companies and the supply chain as a whole"
Weele & Raaij	2014	"SCM typically focuses on the coordination of business functions within and across organizations in a supply chain for the purposes of improving the long-term performance of the individual organizations and the supply chain as a whole"

Though performance is cited as the main objective in the works in Table 1, there is no universally accepted method or metric for its measurement, and it depends on context (Estampe *et al.*, 2013). However, many firms and researchers have employed parameters such as market share, financial benefits, level of perceived product quality, budget accuracy and lead times (Gunasekaran *et al.*, 2004; Chen *et al.*, 2013; Estampe *et al.*, 2013). Stock and Boyer (2009) separate the potential benefits of effective SCM implementation into three categories: 1) value creation; 2) efficiency gains and 3) customer satisfaction.

With the increasing importance of sustainability mentioned previously, many researchers are attempting to incorporate topics of sustainability into research on SCM, resulting in a new thematic area: SSCM (Svensson, 2007). A common definition for sustainability is the utilization of resources to meet the needs of the present without compromising future generations' ability to meet their own needs (WCED, 1987). Thus, SSCM extends traditional SCM to include sustainability topics. Following an extensive review of definitions of SSCM and its related term, green supply chain management (GSCM), Ahi and Searcy (2013) offer the following definition for SSCM which will be used as a point of reference for the purpose of this paper:

> The creation of coordinated supply chains through the voluntary integration of economic, environmental, and social considerations with key inter-organizational business systems designed to efficiently and effectively manage the material, information, and capital flows associated with the procurement, production, and distribution of products or services in order to meet stakeholder requirements and improve the profitability, competitiveness, and resilience of the organization over the short- and long-term. (p. 339)

Here, GSCM is a subset of the broader SSCM which focuses mainly on environmental aspects of SCM. Issues addressed in SSCM include topics related to sustainable business practices, *e.g.* green procurement, reverse logistics, green marketing, eco-design, and corporate social responsibility (for a more complete consideration of topics covered in SSCM research, see Svensson, 2007 and Ashby *et al.*, 2012). As with SCM, performance measurements for SSCM vary widely with context, but include items such as jobs created (social) and GhG emissions (environmental) (Hassini *et al.*, 2012).

Another topic relevant to SCM for the purpose of this review is that of the scope of the supply chain. One of the difficulties in researching sustainable supply chains and supply chains in general is establishing the level of analysis (Miemczyk *et al.*, 2012; Pathak *et al.*, 2014). Miemczyk *et al.* (2012) note that while many studies ostensibly analyze a supply chain, often the unit of analysis is actually restricted to the dyadic (*i.e.*, the relationship between two firms) or the single firm level. In other instances this limitation is imposed intentionally as a means to make research more feasible (Miemczyk *et al.*, 2012). Indeed, in defining the supply chain, Mentzer *et al.* (2001) define three conceptual levels of the supply chain: a direct supply chain which includes a company, a supplier, and a customer; an extended supply chain which also considers the suppliers of the supplier and customers of a customer; and the “ultimate” supply chain which includes all of the organizations involved in the flow of a given product. Defining which portion of a given supply chain to focus on continues to present challenges to researchers and practitioners alike, and can have especially important implications for incorporating sustainable initiatives (Svensson, 2007; Miemczyk *et al.*, 2012; Pathak *et al.*, 2014).

4.2 Life Cycle Assessment

LCA is a process which attempts to quantify all of the environmental impacts of a product during its life cycle. For this reason, it is often referred to as “cradle-to-grave” analysis (Guinhe & Huppes, 1993). Though recorded instances of similar processes of evaluation go back at least as far as 1884, modern versions of the technique began in the late 1960s (Hunt & Franklin, 1996). It gained popularity as a research tool in the 1990s, and became the first and only internationally standardized method for measuring environmental impacts, (Weißenberger *et al.*, 2014) with the most current version of the international standard, published by ISO, being ISO-14040:2006 (ISO, 2006a). In research of environmental impacts, LCA holds many advantages over forms of production-based accounting which focuses on the firm because of its ability to capture true environmental impact levels more accurately (Larsen *et al.*, 2012).

ISO-based LCA consists of four stages: 1) Defining the goal and scope of the LCA; 2) a life cycle inventory analysis phase (LCI); 3) a life cycle impact assessment phase and 4) a life cycle interpretation phase (ISO, 2006a; ISO, 2006b). Important concepts in defining the scope of the study (Phase 1) include specifying data requirements and defining system boundaries. It is important to note that the standard stresses the iterative nature of LCA, and therefore all processes and definitions should be revised as necessary as the assessment progresses (ISO, 2006b). LCI (Phase 2) involves collecting qualitative and quantitative data for the study such as energy inputs and/or GhG emissions and may be measured, calculated or estimated. In the final two stages data is categorized into impact categories (*e.g.*, Climate change) and interpreted (ISO, 2006b).

Of the stages involved in LCA, LCI is cited as being the most resource-intensive, but increasingly online, often public resources are available to reduce the difficulty of performing LCA (Cooper & Fava, 2006). Still, the complexity of performing LCA has been cited as a limitation in its wider adoption (Heiskanen, 2002). In a research context, LCA can present difficulties outside of the product unit of analysis because of the amount of data required (Peters & Solli, 2010).

Though limitations exist LCA can still offer many benefits for supply chain performance. Despite the increasing potential to perform LCA and its popularity in environmental studies, as mentioned previously, its use has been limited in the context of SSCM research, though some studies do exist.

4.3 Evolving Applications of Life Cycle Assessment

An interesting link between LCA and other management concepts exists. Seuring (2004a) notes that several concepts exist that deal with the flow of material and information in the supply chain besides SCM, and these are integrated chain management, industrial symbiosis and life-cycle management (See Table 2). According to Seuring (2004b) integrated chain management is similar to SCM in that it seeks to improve chain performance by managing material and information flows, but uses LCA as its conceptual basis where SCM uses logistics and focuses more on multiple stakeholders. In a review of 50 articles on integrated chain management, Seuring and Müller (2007) conclude that integrated chain management includes many aspects included in SSCM and life cycle management and cite a need to include social aspects. Life-cycle management is also based on LCA but focuses more on the product design phase, as this is where the majority of environmental costs have been identified (Seuring, 2004a). Finally, industrial ecology, in particular industrial symbiosis, is a discipline similar to the previously mentioned concepts in that it focuses on material flows, but tends to adopt a geographical or regional approach to evaluating environmental impacts.

Table 2: Concepts related to the management of materials and information

Concept	Distinctive feature	Actor network	Material flows/system boundaries	Time frame
Integrated chain management	Stakeholder integration	Companies involved in and stakeholders affected by material flows	Material flows within their societal and legal boundaries	Societal and legal systems (decades)
Industrial symbiosis	Geographical approach/regional application	Companies involved in an industrial symbiosis	Material flows in a regional network	Factory life cycle (years to decades)
Life-cycle management	Product design as most important decision phase	All production stages involved in designing and producing products and services	Material flows that are related to a product life cycle	Product life cycle (months to years)
Supply chain management	Managerial activities needed within the actor network	All production stages directly involved in fulfilling customer demands	Operational material and information flows to satisfy customer needs	Supply chain development (months to years); delivery cycle (hours to weeks)

Source: Seuring, 2004a

Further, it has been argued that the most important contribution of LCA is not ISO-14040-style assessments, as these would be and will likely remain impractical for the large number of products produced in the world, but rather a way of thinking (Heiskanen, 2002). These LCA-inspired ideas include design-for-environment or eco-design and life-cycle thinking. Thus, it is recognized that performance improvements in the supply chain can be obtained without the need to perform costly, ISO compliant LCAs. In fact, in a joint effort by the Society of Environmental Toxicology and Chemistry (SETAC) and the United Nations Environmental Programme (UNEP), LCA is just one of many tools available to implement life-cycle thinking (also referred to as having life-cycle orientation) (Life Cycle Initiative, 2013). Despite the obvious connections with life-cycle thinking and SCM, as highlighted by Ashby *et al.* (2012), research on these topics in the context of SSCM is limited.

5. Methodology

The objective of this paper is to explore the links in academic research between a technique developed originally for environmental impact assessments, LCA, and the pursuit of improved performance at the supply chain level, SCM.

A systematic literature review is a research method with origins in the field of medicine used to synthesize and advance research (Tranfield *et al.*, 2003). Broadly, a literature review serves to identify the state of the art of a given topic, exploring methodologies, theories, and key research issues in a manner which allows for the advancement of the field (Hart, 1998). Research questions can be developed from it, as well as the appropriateness of the topic for academic research and the motivation to undertake further studies (Hart, 1998; Webster & Watson, 2002). Given the disparate nature of the subject of interest, a literature review represents an appropriate tool for beginning to establish the place of LCA within supply chain management studies.

However, especially in the field of management, the traditional literature review may suffer from methodological weaknesses that ultimately can result in incomplete representations of a given topic. A researcher may, or almost surely *is*, subject to bias which can lead to arbitrary or implicit criteria for search techniques, inclusion criteria, and interpretation of results (Cook *et al.*, 1997). The systematic literature has emerged in response to such weaknesses. In contrast to a traditional literature review, the systematic literature review attempts to follow a more scientific process which can be imitated and audited.

This paper employs the systematic literature review process suggested by Tranfield *et al.* (2003, p. 214) which applies the multi-stage reviews described below accepted in the field of medicine to business studies. Those reviews, encouraged by the National Health Service of Great Britain (NHS, 2001, as cited by Tranfield *et al.*, 2003) consists of three stages: 1) Planning; 2) Conducting, and 3) Reporting and dissemination. This system of review has been used in other recent papers on supply chain management (*e.g.* Ahi & Searcy, 2013; Ashby *et al.*, 2013).

Several steps are recommended to establish appropriate search terms and techniques when planning a systematic literature review. The need for the review was identified through extensive topic exploration, including a preliminary review of literature on the topic of Life Cycle Assessment in ISI Web of Knowledge database. It also included the review of several relevant initiatives by international organizations. Time limitations only allowed for minimal consultations with experts, which could have served to better shape the search technique. However, it is the hope of the author that sufficient documentation of search methods will allow such a limitation to be easily addressed in future research. Following Tranfield *et al.* (2003) and in line with the often exploratory nature of reviews in management studies, a general objective was developed for this project and was kept intentionally broad to allow for sufficient exploration of the topic.

The specific search terms for the review were determined through an initial scoping study followed by a preliminary literature review. Building from an extensive literature review by Ashby *et al.* (2012) which identified LCA in supply chain management studies as a potential knowledge gap, the author performed an initial exploration of topics in the supply chain literature which incorporate LCA. As reviewed previously, Seuring (2004a), provides the justification for several related search terms from concepts which incorporate LCA and were included as search terms. These were Life Cycle Management (LCM) and Life Cycle Integration (LCI). As the objective was to see the intersection between LCA in supply chain management studies, the terms “Supply Chain Management” (SCM), “Sustainable Supply Chain Management” (SSCM), and “green supply chain management” (GSCM) were also employed. Scopus was selected as the academic database because it has been cited as being broad in its coverage of management and engineering journals (Ahi & Searcy, 2013). However, given the relatively low number of initial results which focused on SCM as defined in this paper, Emerald Insight and ISI Web of Knowledge were later included to increase the number of articles evaluated. This initial search returned a total of 306 results. After removing for duplicates and removing results which contained erroneous search terms (*e.g.* removing “Storm-drain control management” results), 48 articles were identified for review. Of these, a final number of 39 were accessible and downloaded for analysis.

Sandelowski *et al.* (1997) caution that the use of checklists to determine the quality of studies for review can exclude pertinent results and that therefore, at a minimum, researchers should justify any articles they leave out. To be sure to avoid any subjectivism in the exclusion of papers based on perceived quality of the articles, all results which appeared in the database search, included the selected keywords and were available for download were included.

6. Analysis of Results

As encouraged by Tranfield *et al.* (2003), systematic reviews should make research more comprehensible for the practitioner through the synthesis of the reviewed research. They recommend dividing reviews into two sections: a broad, descriptive analysis and a more in-depth thematic analysis. Following the recommendation of those authors, the following section describes the results of the evaluation of the analyzed articles. First, a general summary is presented with information such as the publisher of the study, the type of document, and the methodologies employed. Following is a thematic analysis of the articles based on one of three classifications based on the role of LCA in the research.

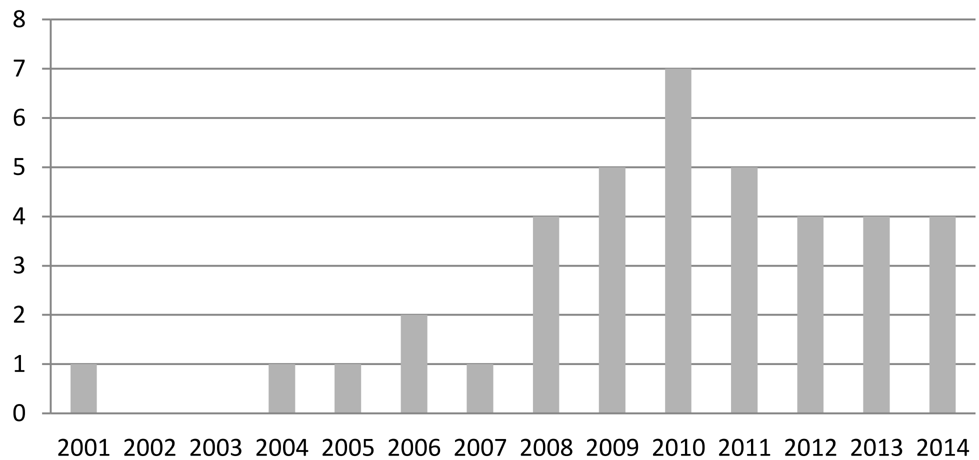
6.1 Summary of Findings

Table 3: Reviewed Publications by Source

Paper Source	Publication Type	Number of Publications
Journal of Cleaner Production	Academic Journal	5
Environmental Science and Technology	Academic Journal	5
Journal of Industrial Ecology	Academic Journal	4
Computers in Industry	Academic Journal	3
Chemical Engineering Science	Academic Journal	2
AIChE Journal	Academic Journal	2
Computers and Chemical Engineering	Academic Journal	2
Intelligent Decision Technologies	Academic Journal	1
Transportation Research Part E: Logistics and Transportation Review	Academic Journal	1
International Conference on Management Science and Engineering - Annual Conference Proceedings	Conference Proceedings	1
WSEAS Transactions on Environment and Development	Academic Journal	1
Journal of Environmental Management	Academic Journal	1
International Journal of Sustainability in Higher Education	Academic Journal	1
Clean Technologies and Environmental Policy	Academic Journal	1
International Journal of Production Economics	Academic Journal	1
International Journal of Production Research	Academic Journal	1
Procedia CIRP	Academic Journal	1
Expert Systems with Applications	Academic Journal	1
Robotics and Computer-Integrated Manufacturing	Academic Journal	1
Proceedings of the 4th IEEE International Conference on Management of Innovation and Technology, ICMIT	Conference Proceedings	1
IIE Annual Conference and Expo 2007 - Industrial Engineering's Critical Role in a Flat World - Conference Proceedings	Conference Proceedings	1
Proceedings - 2010 IEEE International Conference on Emergency Management and Management Sciences, ICEMMS 2010	Conference Proceedings	1
Decision Support Systems	Academic Journal	1

Table 3 includes the journals and sources of the papers that were evaluated for the review. As was to be expected given the background of the subject matter, the results include journals from a wide range of disciplines, including computer and environmental sciences. Given that LCA has been traditionally used as a means of evaluating environmental costs, it is not surprising to find that the three journals with the most results are from the industrial ecology and environmental science areas. Further, as shown in Figure 1, all results were from after the year 2000, highlighting the newness of the integration of LCA into supply chain management study. An obvious feature of the graph is a large number of works from the year 2010. Though the author explored possible explanations for the surge in that year, no satisfactory explanation could be identified, though two works using modeling were published by the same author (Guillen-Gosalbez G., Grossmann I., 2010; Guillen-Gosalbez *et al.*, 2010).

Figure 1: Number of publications per year



As far as the country of publication (Table 2), the United States was the country with the most publications, with a large number of publications coming from Europe (14) and East Asia (9). That so few results came from Germany is troubling given the review of literature on the topic in that country by Seuring and Müller (2007), suggesting that perhaps more search terms should have been incorporated for a more comprehensive set of results.

Table 2: Country of Publication of Corresponding Author

Country	Number of Papers
USA	11
Spain	7
China	5
Italy	2
Switzerland	2
Iran	1
Singapore	1
Norway	1
Canada	1
United Arab Emirates	1

Japan	1
Germany	1
Argentina	1
Taiwan	1
South Africa	1
Republic of Korea	1
The Netherlands	1
Papers with authors collaborating internationally:	7

Research methodologies were tracked according to the groupings found in the literature review on SSCM by Ashby *et al.* (2012) in Table 3. The vast majority of the studies analyzed employed case studies as their methodology of choice, often in combination with mathematical modeling. In fact, only one paper used only modeling (Marquez & Blanchar, 2006) without later applying the concepts to a particular case study. That so many studies incorporating LCA should use the case study method supports the notion that LCA is complicated and LCA takes a lot of work. Standardized environmental measures such as Eco-indicator 99 exist, but there is no universally accepted measure, and thus comparing studies even of highly similar products proves challenging. Though the ISO-14040 standard attempts to provide guidelines for the use of LCA, it is still problematic to move outside of case studies (for example, applying LCA to several firms). A technique called Economic Input-Output LCA (EIO-LCA) may offer a way to do this, as exemplified in Brent and Visser (2005) considered later. It also is important to note that "Survey" in Table 3 refers to questionnaires sent to human subjects and not to environmental surveys or estimates, which are an essential step in ISO-14040 type LCA to determine environmental impacts (ISO, 2006).

Table 3: Methodologies of reviewed papers

Methodology	Frequency Employed
Case Study	29
Modelling	18
Interviewing	8
Theory / Concept Development	6
Survey	4
Literature Review	3

Table 4: Industries of Study

Industry	Number of Papers
Agrifoods Sector	6
Chemicals	5
Automotive Industry	5
Electronics Manufacturing	4
Energy	2
Multiple / General Application	2
High-Tech	2
Household Products	2
Paper Manufacturing	1
Health Care	1
Education	1
Furniture Sector	1
Publishing	1
E-Commerce	1
Logistics	1
Purely Conceptual	4

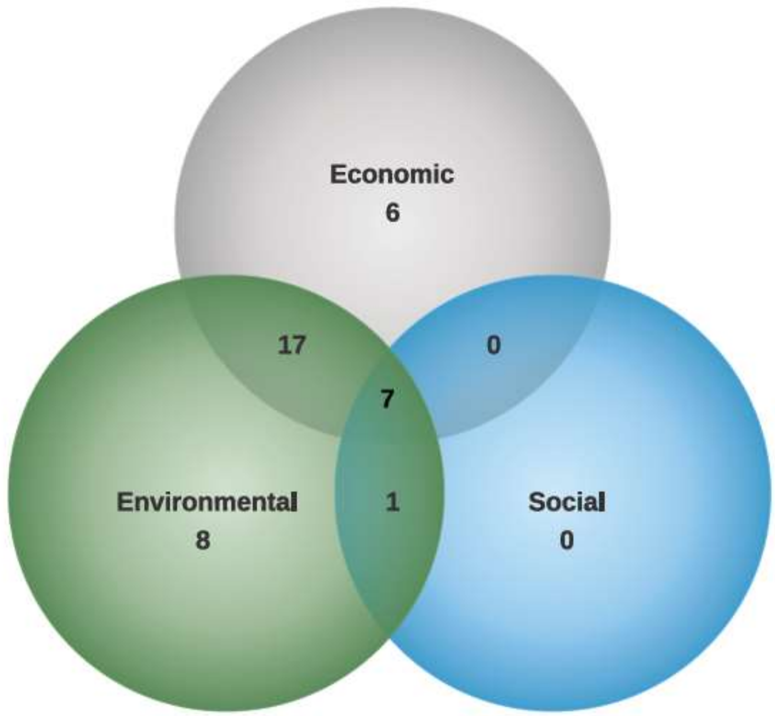
Papers were also grouped according to industry. These were either mentioned explicitly in the analyzed study or, in the case of specific products (*e.g.*, diapers), classified by the author in accordance with the United States Bureau of Labor Statistics (United States Department of Labor, 2014). Half of the research concentrated on 4 sectors: the agrifoods sector, chemical production, the automotive industry, and electronics manufacturing. The rest of the papers were spread across a wide-range of other industries, in part emphasizing the flexibility of LCA (in the cases in which it was employed). 4 papers were purely conceptual.

6.2 Thematic Analysis

In order to give structure to the wide ranging topics covered in the articles reviewed, the articles were grouped according to their area of focus in terms of sustainability (Figure 2). As mentioned previously, LCA is closely linked to the concept of sustainability, which itself is more and more becoming integrated with supply chain management. Three overarching elements of sustainability were chosen: 1) the economic element; 2) the environmental element and 3) the social element, collectively referred to often in business sustainability writing as the Triple Bottom Line (TBL). The use of these three elements in studies of sustainability in SCM is frequent in recent research (*e.g.* Maxwell & van der Vorst, 2003; Gmelin & Seuring, 2013; Beske *et al.*, 2013). Although the 7 characteristics identified in Ahi & Searcy (2013) were also considered for grouping, in the end given the relatively small number of articles it was decided that such a level of nuance was unnecessary for a complete consideration of the subject.

The articles were categorized based on either their explicit or implicit sustainability focus. Admittedly, this method of categorization was subject to researcher bias and so it would have been beneficial for an informed expert to also classify the articles as a means to reduce subjectivity, but this was not possible given resource constraints.

Figure 2: Number of Articles Based on Primary Focus of Research



N = 39

Figure 2 shows a clear dominance of articles which focus on economic and environmental issues, whereas a much smaller portion of articles address social issues. Given the traditionally environmental use of the technique it may not be surprising that no articles focus exclusively on social issues, and yet only one focuses on the incorporation of social issues with environmental ones. 8 articles were considered to address all three elements of sustainability. Interestingly, the distribution of the articles would suggest that, at least within papers that incorporate LCA, the observation by Asif *et al.* (2008) that only a very small portion of papers on SSCM address topics other than strictly environmental sustainability does not apply to the LCA-SCM intersect.

In the following paragraphs, the common themes and contributions of the papers analyzed in this review will be considered according to their grouping (Table 5 lists the authors by group).

Table 5: Articles by Sustainability Focus

Focus	Number of Papers	Citations
Environmental	8	Matthews *et al.*, 2008 Koehler & Wildbolz, 2009 Cao *et al.*, 2011 Thurston & Eckelman, 2011 Cellura *et al.*, 2012 Stoessel *et al.*, 2012 Xu *et al.*, 2013 Cohen & Ramaswami, 2014
Economic	6	Marquez & Blanchar, 2006 Sandborn, 2007 Gulledge *et al.*, 2010 Do & Chae, 2011 Marchetta *et al.*, 2011
Environmental and Economic	17	Shaft *et al.*, 2001 Kainuma & Tawara, 2006 Abukhader, 2008 Lai *et al.*, 2008 Early *et al.*, 2009 Guillen-Gosalbez & Grossmann, 2009 Guillen-Gosalbez & Grossmann, 2010 Guillen-Gosalbez *et al.*, 2010 Kuo, 2010 Michelsen & Fet, 2010 Taghaboni-Dutta *et al.*, 2010 Adhitya *et al.*, 2011 Pozo *et al.*, 2012 Tseng & Geng, 2012 Ruiz-Femenia *et al.*, 2013 Liu *et al.*, 2014 Manzardo *et al.*, 2014
Environmental and Social	1	Andrews *et al.*, 2009
Environmental, Economic and Social	8	Zhu & Cote, 2004 Brent & Visser, 2005 Asif *et al.*, 2008 Bojarski *et al.*, 2009 Wang & Fu, 2010 Chun & Bidanda, 2013 Silcher *et al.*, 2013 Pishvaee *et al.*, 2014

6.2.1 Environmental Focus Group

Following the most classical interpretation of LCA, the papers in this group focused nearly exclusively on addressing environmental impacts in supply chains through the use of LCA, where any economic analysis was used only as a means to accomplish this goal. For example, Thurston and Eckelman (2011) use Economic Input-Output LCA (EIO-LCA) to translate aggregated university purchases into an environmental impact evaluation. In all of the cases, researchers remained methodologically close to the ISO-14040 style of LCA. Also important to note was the near universal use of implicit definitions for “supply chain” and “supply chain management”, despite this being a central theme in the papers and appearing as one of their keywords. In fact, only one article, that of Cellura *et al.* (2012), expressly defines supply chain management as a “set of supply chain management policies held, actions taken, and relationships formed in response to concerns related to the natural environment with regard to the design, acquisition, production, distribution, use, reuse, and disposal of the firm’s goods and services” (citing Zsidisin and Siferd, 2001). Thus, a certain amount of ambiguity can be found in the articles, as is common in the multi-disciplinary field of supply chain management (Mentzer *et al.*, 2001; Zacharia *et al.*, 2014). Despite this ambiguity, the rigor required in employing LCA such as establishing clear system boundaries as considered in Cao *et al.* (2011), Cellura *et al.* (2012), Koehler & Wildbolz (2009), and Xu *et al.* (2013) does allow the reader to make educated guesses about their meaning of the term.

In general, these articles contribute to the literature on the use of LCA, often in combination with other techniques, as a means to inform decisions to improve the environmental sustainability of supply chains at the life cycle level. What is more, LCA is preferable to other, internationally established protocols (*e.g.*, the Kyoto Protocol) because it more accurately measures impacts (Matthews *et al.*, 2008). However, as is true with many other articles analyzed as a part of this review, the complexity involved in performing and analyzing LCAs is an issue (*e.g.*, Cohen & Ramaswami, 2014). Stoessel *et al.* (2012) further suggest that presenting LCA results to consumers will present a significant challenge for this same reason, and caution against the use of labels containing too much environmental information. However, one paper (Thurston & Eckelman, 2011) with an environmental focus stresses that complexity need not impede the use of at least basic LCA to guide decision making processes. Using EIO-LCA with a combination of university purchase information and data publicly available in online databases, these authors are able to present estimated direct and indirect environmental impacts of purchasing decisions. They further note that by using EIO-LCA it would take relatively little effort for reports to be created showing environmental impacts along with economic information for business use.

6.2.2 Economic Focus Group

The economically focused group of articles was unique in this analysis, not just because of their exclusive focus on economic issues but also in that they included a concept that was found to come from outside the LCA and LCA-inspired disciplines, that of Product Life Cycle Management (PLM). While the term includes the words “Life Cycle Management” as explored by Seuring (2004) and mentioned previously, in fact the concept comes from studies in product management, with a special focus on the role of information technology (Grieves and Tanniru, 2008) and has no direct connection to LCA. Further, its goals include the maximization of product value for customers, the reduction of costs, and the increase of revenues (Stark, 2005).

Because PLM seemingly falls outside of the objective of this paper, it was considered to remove them all together from the analysis, but the potential implications and linkages for LCA-style analysis, as highlighted by its potential role in sustainable product development as explored by Gmelin and Seuring (2014) was deemed sufficient justification for their inclusion. [Consider moving this to the Methodology Section]. Despite the papers in this group falling outside the intended scope of the review, they contain many topics which are highly relevant for the implementation of life-cycle thinking in supply chains. They address a central issue in many of the articles which use LCA: how to manage a large amount of data spanning the supply chain in a way to make informed decisions. Indeed, in a case study of the Swedish logistics firm ASG, Shaft *et al.* (2002) cite information systems as being critical to the success of Life-Cycle Management initiatives.

The principal contributions of the articles in this group address IT issues or the integration of IT with other functions. For example, Do and Chae (2011) address integrating software and hardware development using a product data management system which allows engineers to collaborate via technology, thus improving efficiency and reducing errors in production. Examining the automotive industry, Marchetta *et al.* (2011) also focus on coordination, attempting to establish a reference framework for PLM. Gulledge *et al.* (2010) follow with another work on coordination, this time centering on condition-based maintenance, defined by the authors as “form of proactive equipment maintenance that forecasts incipient failures based on a real-time assessment of equipment condition obtained from embedded sensors and or external tests and measurements that are extracted directly from the equipment". They conclude that many firms can progressively implement condition-based maintenance at the life-cycle level to accurately perform product and process improvements. This can be a major advantage to firms, where technology infrastructure struggles to adapt quickly enough in response to business process changes.

Finally, Sanborn (2007) addresses obsolescence management, *i.e.* managing for the obsolescence of components and technologies that many products in a system depend on. Sandborn predicts that the issue of obsolescence will continue to grow as more and more products rely on components in their supply chain that they do not control. The author covers actions that managers can take in response to this phenomenon, beginning with early planning for system sustainment. Such actions, he argues, can have a number of beneficial effects, including more accurate allocation of budget, improved operational availability, and the increased opportunity for shared solutions across multiple systems.

6.2.3 Environmental and Economic Focus Group

The papers with an environmental and an economic focus made up the largest group of papers evaluated in the review. In content, many of the themes were similar to that of the environmentally focused group, especially the issue of complexity, which could have been exacerbated by the addition of economic performance indicators. Often, these were apparent in multi-objective optimization problems (*e.g.* Guillén-Gosalbez & Grossmann, 2009; Ruiz-Femenia *et al.*, 2013). However, links also existed with the economically oriented PLM group of articles, in that in many articles the role of appropriate IT infrastructure is critical, especially to develop practical decision making tools (*e.g.* Shaft *et al.*, 2001; Early *et al.*, 2009). Articles in this group often explicitly considered the viewpoint of the supply chain manager with multiple objectives (*e.g.*, Kainuma & Tawara).

Several key contributions to LCA-SCM literature were made in these papers. A large portion of the research concluded that LCA-based tools could be used to assist practitioners in making informed decisions when considering the economic and environmental impacts of a given managerial action. Several studies employed the use of multi-objective optimization to model different scenarios given a set of environmental and economic inputs. This was the case of Guillén-Gosalbez *et al.* (2010) who concluded that not only could such modeling inform decision makers, it also improved upon other environmental techniques which focused on the plant-level by detecting environmental impacts typically left out of those assessments. Further, the models could incorporate a high number of factors, including demand uncertainty (Guillén-Gosalbez, 2010; Ruiz-Femenia *et al.*, 2013). In a similar vein, two articles employed Multicriteria dimension analysis (MCDA), a technique for addressing multiple objectives in decision making (Liu *et al.*, 2014; Manzardo *et al.*, 2014). Though it offers the advantage of giving decision makers the ability to rate the importance of multiple criteria, in both articles it is recognized that the technique requires a high level of technical skill to carry out. Manzardo *et al.* (2014) address this partially by limiting the number of environmental factors to analyze.

Michelsen and Fet (2010), recognizing the difficulties of employing LCA in SMEs, examine Norwegian furniture manufacturers and find that LCA in combination with Life-Cycle Costing is effective at identifying potential ways to increase environmental efficiency while considering the associated economic cost. However, they note that in their particular case, the greatest improvement in environmental efficiency was only 16% according to their criteria. In a more basic application of LCA, Kuo (2010) concludes that firms can reduce costs as well as environmental impact simply by considering the End-of-Life product stage at production. According to the paper, these considerations can lead to more efficient recycling and disposal.

As mentioned previously, a prevalent issue in many of the papers analyzed in the literature review is that of the complexity involved in analyses involving LCA. Lai *et al.* (2008) stress that for meaningful, accurate results the data collection stage is critical, and yet gathering environmental data can be quite challenging. Several authors recognize that this can limit its practicality for practitioners, and some present means of overcoming these difficulties (*e.g.*, Kainuma & Tawara, 2006; Michelsen & Fet, 2010). To reduce the number of variables to consider Pozo *et al.* (2012) propose applying principal component analysis, and demonstrate its use in a case study of chemical supply chains. Several works use Eco-indicator 99 to measure environmental performance, a tool which returns a score based on 11 environmental categories (Lai *et al.*, 2008; Guillen-Gosalbez & Grossmann, 2009; Guillen-Gosalbez & Grossmann, 2010; Guillen-Gosalbez *et al.*, 2010). Using prefabricated, accepted indicators can simplify the LCA process by removing the need for practitioners to evaluate the weightings of environmental impacts. However, Pozo *et al.* (2012) note that the use of “pre-weighted” environmental impacts such as the Eco-indicator 99 has drawbacks, mainly in that the weights may not align to the needs of the practitioner in a particular situation.

The central role of IT in utilizing LCA to aid decision making is explored as well. Citing the need for information sharing in supply chains, Taghaboni-Dutta *et al.* (2010) develop a web-based hub to facilitate sharing of data across supply chain members to allow for improved economic and environmental supply chain performance. Early *et al.* (2009) explore a similar system used by Toyota Motor Sales which incorporates basic Life Cycle Costing with LCA information which allowed the company to reduce environmental impacts and costs from packaging and distribution. However, these authors recognize that while the use of the tool is easy to use for practitioners, its maintenance requires more expertise. This implies that the critical task of keeping life cycle inventories up to date would require expert intervention.

Finally, practitioners can take less IT-intensive actions to reduce the complexity of LCA. The importance of clearly establishing system boundaries for analysis is cited as a way to increase the applicability of LCA techniques (Lai *et al.*, 2008; Liu *et al.*, 2014). Lai *et al.* (2008) note that the needs of an operations manager may not necessitate a complete product-level LCA because much of the information falls well outside the manager's control and because the manager is typically focused on improving an existing situation. In their article, the authors limit their system boundary to material flows. Finally, Michelsen and Fet (2010) note that even firms with limited resources can implement life-cycle management to improve environmental performance using a three-step process which includes the use of LCA and life cycle costing. Even without LCA experts on hand, a number of tools exist to perform such analyses. The authors also note that where such tools have not yet been developed, extensive databases exist (the authors list several), often at no cost, which can greatly simplify the LCA process.

6.2.4 Environmental and Social Focus Group

Only one article was found that focused on environmental and social issues through the use of LCA. Andrews *et al.* (2009) apply a technique called Life Cycle Attribute Assessment to a case study of a tomato company and were able to identify critical areas the company could focus on to improve environmental and social performance, measured through a number of indicators such as offering health insurance, offering livable wages, and producing locally. The authors stress that the link between corporate social responsibility and LCA should be strengthened. Here, the authors also cite a field which could be of further interest to supply chain managers: social life cycle assessment (SLCA).

6.2.5 Environmental, Social and Economic Focus Group

The 7 papers that combine environmental, social and economic aspects in their research can be divided by their methodologies. Two articles, those of Chun and Bidanda (2013) and Asif *et al.* (2008) are purely conceptual papers, yet offer important insights into research which seeks to utilize these three aspects of sustainability. Asif *et al.* (2008) stress that LCA is a part of the sustainability framework, and not visa-versa, and that researchers should always strive for a "three-pronged" approach when exploring sustainability themes. In examining the origins of sustainable manufacturing studies, Chun and Bidanda (2013) highlight the need for transparency in manufacturing processes. They cite a desire for sustainable consumption on the part of consumers that is not always met by manufacturers, and a need for clarity in eco-labeling schemes.

As with other articles that formed a part of this review, mathematical modeling was employed as a means to come to conclusions about sustainable supply chain management. Bojarski *et al.* (2009) explore the benefits of incorporating LCA in modeling as a means for not only improved sustainable supply chain performance, but also as an important step in effective policy design. Not doing so, they caution, can lead to often unexpected results (in the case of chemical production, firms may opt for the use of alternative chemicals to reduce CO^2 emissions which affect the environment in different ways). Pishvaee *et al.* (2014) use modeling similar to that of the works in the environmental and economic focus group, but incorporate social aspects such as job creation, health and safety. The authors apply the model to a medical supply chain and conclude that significant improvements can be made through the use of such models, especially by focusing on the end-of-life stage.

One study (Brent & Visser, 2005) has potential implications for limiting the complexity of LCA. Analyzing first-tier suppliers of a South African automotive company, the authors highlight that, at least in the context of their study, performing life-cycle inventories at a regional level would not influence LCA results significantly. Lastly, Zhu and Cote (2004) examines the case of a major Chinese sugar complex in its efforts to implement sustainable supply chain improvements. They note that in its initiative the group has made great gains in information sharing among supply chain members, but cite an under-appreciation for supplier diversity as a major challenge for the group.

7. Conclusions

In this paper, a systematic literature review was used to examine the link between life cycle assessment (LCA) and supply chain management (SCM) in order to examine its potential applications for practitioners. After defining the relevant terminology, articles were classified by year of publication, methodology employed, industry studied, and sustainability focus. Later, the content of articles was analyzed to identify key themes. LCA and LCA-inspired thinking is recognized as a way to gain valuable insight into improving sustainable supply chain performance.

However, as was expected based on the initial literature review, the complexity involved in performing LCA was recognized as a major hindrance to its use in SCM. However, several articles addressed ways to reduce complexity to make the use of LCA more practical. Often, LCA in practice took on the form of life-cycle thinking, in which sustainable supply chain performance could be improved by adopting a holistic view of product production without necessarily requiring in-depth analysis. The potential role of information technology to facilitate the adoption of LCA was also explored, both as a means of increasing the accuracy and usability of analyses and as a means of making such analyses easier to perform.

Therefore, the works reviewed suggest that practitioners can gain from adopting LCA and life-cycle thinking in their operations, not only to reduce environmental impacts at the supply chain level but also to potentially positively affect economic and social performance. In the least, it can offer a method for weighing alternatives for economic, social and environmental costs. LCA is cited as being the most comprehensive form of environmental analysis when performed according to ISO standards. Still, companies with limited resources can still gain from relatively simple analyses, often at low costs by taking advantage of existing LCA databases and online tools. Also, firms which have already adopted life-cycle thinking, including the use of LCA, can see their benefits increase by focusing on the key role of IT and by concentrating on operational system boundaries.

8. Limitations and Future Research Directions

Although the results of this literature review are noteworthy, several limitations must be recognized. First, many of the classifications, including the classification by industry and by sustainability focus, ultimately relied on the author's subjective judgment of the papers reviewed. Therefore, it would have been beneficial to the study to have used methods which reduced this subjectivity such as having a second researcher to aid in classification.

Second, it is important to recognize that many articles that deal with life cycle thinking and LCA applied in supply chain management studies may have been left out of this review. A more comprehensive review could be performed by expanding the search to include the abstract or by including articles cited by authors in the review. However, given the time restrictions in this review a more comprehensive review was not possible. This review should therefore be viewed as more orientative rather than comprehensive.

Despite these limitations, a number of research directions can be developed from the study. One of the clearest shortcomings in the reviewed research, as several of the authors recognized, was the lack of the inclusion of social indicators. This has also been observed in SCM studies in general, and could be addressed in future research. Another potential area for research is the integration of social and environmental indicators in Product Life Cycle Management. Much could be gained from a unification of these fields, as they have much in common. Lastly, future research needs to address appropriate definitions of system boundaries for life-cycle management. Though this task is a crucial step in LCA, in much of the research observed it received little or no attention. Coming to an accepted way of defining system boundaries could increase the practicality of incorporating LCA for practitioners.

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10. Appendix: Reviewed Papers

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