Title

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Journal
Journal of Industrial Ecology, 22(1)

ISSN
1088-1980

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Publication Date
2018-02-01

DOI
10.1111/jiec.12550

Peer reviewed

Same Supply Chain, Different Models: Integrating Perspectives from Life-Cycle Assessment and Supply Chain Management

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Summary

Within Industrial Ecology, there is a substantial community focusing on Life-Cycle Assessment and corresponding tools and methods. Within the field of supply chain management, an increasing community is converging around sustainable supply chains. These two communities study the same underlying systems, but bring different perspectives to bear. We review seven issues that arise at this intersection of life-cycle assessment and supply chain management, with the aim of illustrating how both communities can enrich each other by closer interaction. We conclude with some suggestions for how the two communities can further collaborate.

Keywords: LCA, supply chain, operations management, industrial ecology

Introduction

Consider the following questions: Should a ski jacket that is sold at a discount in the post-season sale be allocated a lower carbon footprint than a physically identical jacket sold earlier at full price? If the global warming potential (GWP) of one functional unit of a product is 10 kg CO_2-equivalent when making 1,000 units, is the GWP still 10 kg/unit when making 2,000 units, or more, or less? Can GWP per unit be increasing in volume while eco-toxicity goes down? Can it be desirable to double-count emissions when allocating them to multiple firms in a supply chain?

None of these questions has easy answers, but they are examples of the kinds of issues that arise at the interface of life-cycle assessment (LCA) and supply chain management (SCM). A subset of scholars in both fields ultimately aim to improve sustainability in supply chains, but do so coming from diverging perspectives. Much of the work in LCA draws on physical and life sciences and systems engineering, while that in supply chain management area draws on operations research and economics. These two perspectives do not conflict with one another, but they do cast a different light on the same issues. Over the years, the authors have engaged with the operations management and supply chain management community, as well as with scholars in the industrial ecology (IE) community including those focusing on LCA. We have been struck by how much the two communities have in common, but also by how little overlap there is in practical terms, even though some of the interrelationships between the fields and the limited amount of border crossing between them was already highlighted by Seuring (2004). The aim of this article is twofold: first, to help bridge the gap between the two communities, by highlighting ways in which they tend to take different perspectives on the same underlying supply chain, leading to questions such as those above. Second, to suggest ways scientists from the two disciplines can complement each other's work.

Although carbon footprinting is a much narrower and less mature domain than LCA, it has caught on in the SCM community, and is hence helping to create a bridge to LCA. In what follows, we recap why LCA and carbon footprinting are important tools in supply chain management. In order to better understand the differences between the LCA and SCM perspectives, we first provide brief impressionistic histories of both fields. After that, we review seven ways in which the modeling approaches underlying LCA and SCM diverge, and suggest implications of each. Generalizing is always dangerous and we do not imply that every study or every individual researcher in LCA or in supply chain management fits our respective characterizations. Nevertheless, we hope that our high-level stereotyping does help individuals in both communities better understand each other's viewpoint.

Short Histories of Industrial Ecology and Sustainable Supply Chain Management

In this section, we first recap why life-cycle thinking is increasingly seen as crucial in supply chains in practice. After that, we briefly sketch the history of the academic disciplines of LCA and of SCM, to set the stage for our discussion of how the LCA modeling approaches differ from those in the SCM area. As such, these sketches are impressionistic rather than comprehensive.

Why Is Life-Cycle Assessment Important in Supply Chains?

Businesses and regulators are showing increasing interest in industrial ecology concepts and methods such as LCA and carbon footprinting. In order to weigh products' environmental, economic and social consequences appropriately, agencies need to understand the full impacts of products when considering new regulations. Appropriate design of product take-back legislation, including whether to focus on recycling or remanufacturing, requires an appreciation of the full range of environmental impacts throughout the supply chain (Atasu et al. 2009; Gui et al. 2013). Other regulations such as RoHS and REACH (on hazardous substances and chemicals), Dodd-Frank Section 1502 and California's SB 861 (on conflict minerals), various emissions trading schemes, and many others, all have supply chain-wide implications. To comply with those regulations, businesses often need to conduct their own LCA (or similar) studies.

Other reasons for firms to engage in LCA and carbon footprinting include the increasing demands for voluntary disclosure, such as orchestrated by CDP (formerly the Carbon Disclosure Project), the GRI (Global Reporting Initiative), or SASB (Sustainability Accounting Standards Board). Firms considering applying for eco-labels will want to understand the environmental, social and economic consequences of doing so. Customers are asking suppliers to disclose more information about their products and processes, individually (as Walmart and many others do) or through trade associations (as Nike and Patagonia and others do through the Sustainable Apparel Coalition). Firms also engage in carbon footprinting as a way to identify opportunities for cost savings, as carbon hotspots often point to opportunities for profitable energy efficiency initiatives. Matthews et al. (2008) estimate that on average 74% of a firm's carbon footprint falls in its upstream supply chain, though Blanco et al. (2016) estimate that US firms that reported any Scope 3 emissions at all as part of their CDP disclosures in 2013 only reported 22% of what would be expected based on Matthews et al. (2008). Given this variety of reasons to conduct a LCA or carbon footprint, there is a similar multitude of ways to do so. Although we do not aim to define "LCA" or "carbon footprinting" narrowly, the definitions by ISO are helpful. The ISO standard 14040:2006 defines LCA as a "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle". The ISO/TS standard 14067:2013 defines the carbon footprint of a product as the "sum of greenhouse gas emissions and removals in a product system, expressed as CO_2equivalents and based on a life cycle assessment using the single impact category of climate change" (emphases and references removed).

Supply Chain Management: A Brief History

To understand the predominant perspective of research in sustainable supply chain management, it is informative to trace the evolution of the broader field to which it belongs, that of Operations Management (OM). One can dispute the exact origins of the OM discipline, but Frederick Taylor's (1911) work on scientific management is often considered one of the foundations, with its focus on applying scientific principles to production processes in order to improve their efficiency and effectiveness. That process-based perspective is still central to much of the OM field today, though the scope of the processes studied has gradually increased over time (as described in Corbett and Klassen 2006). For instance, the subfield of quality control initially (in the 1920s and 1930s) focused on reducing defects at a single process step. During the 1970s and 1980s, several interrelated movements such as Total Quality Management and Just-In-Time expanded that view: they considered various types of waste to be a form of defect, including waste of time, waste of movement, waste of space, etc. They also extended from viewing a single process to taking into account the needs of downstream processes and the capabilities of upstream processes. Any approach to improving processes starts with mapping the process flow and measuring its performance along several key metrics. It is only a small step from there to consider resource use and environmental impacts as a form of defect, and to use the same mapping and measurement approach to reducing those impacts, as argued in (among many others) Klassen and McLaughlin (1993). The parallel with LCA is obvious.

Another large subfield in operations management deals with supply chains, an area which has also seen a gradual expansion in scope. This can be traced back to early work on managing inventory levels when replenishment occurs in batches (early 1900s) and/or when demand is uncertain (1950s), and to a different stream of work focused on optimal design and operation of distribution systems. Since the 1990s, supply chain management has come to encompass managing inventories and flows of products and information across many stages in supply chains managed by separate entities, which need to find ways of coordinating their decisions while optimizing their own profits (Chen 2002, Disney and Lambrecht 2007). A substantial portion of this field, and the part that we focus on here, draws on models from operations research and economics to improve performance of supply chains. As the scope extends from a single process to coordinating multiple processes within a firm to coordinating across multiple firms, it is again only a small step to include raw materials management and reuse and end-of-life considerations into the "extended" supply chain framework. This stream is often referred to as closed-loop supply chains (but also reverse logistics and other names) and started emerging in the late 1990s, paralleling the focus inherent in LCA; see for instance Ferguson (2010) or Guide and Van Wassenhove (2003) for reviews.

The term "sustainable supply chain management" (SSCM) is also used in the literature; in fact, the review by Ahi and Searcy (2013) uncovers 12 different definitions. Pagell and Shevchenko (2014, p. 45) define sustainable supply chain management as "all SCM research that addresses the environmental or social components of performance [...]", and go on to argue that eventually *all* research in SCM should be sustainable. Seuring and Müller (2008) offer an analogous definition, and argue that sustainable supply chain management has to take into account a wider range of issues, a longer part of the supply chain, and use a wider set of (environmental and social) performance metrics. The desired forms of sustainable supply chain management, as characterized by Pagell and Shevchenko (2014) and Seuring and Müller (2008), are of course already much more closely aligned with LCA than is true for the SCM field more broadly. For instance, Beske and Seuring (2014, p. 327) argue that the most advanced stages of sustainable SCM would include LCA.

For more on sustainable operations generally, see for instance Angell and Klassen (1999), Kleindorfer et al. (2005), and Corbett and Klassen (2006). For more on sustainable supply chains specifically, see for instance Linton et al. (2007), Srivastava (2007), Seuring and Müller (2008), and Bouchery et al. (2016). For more on the field of closed-loop supply chains, see for instance Fleischmann et al. (1997), Carter and Ellram (1998), Guide (2000), Dekker et al. (2004), Flapper et al. (2005), and Ferguson (2009).

Industrial Ecology and Life Cycle Assessment: A Brief History

The field of LCA has developed rapidly since the 1980s (see Finnveden et al. 2009 and Guinée et al. 2011 for reviews). From simple energy analysis in the early 1970s to more complex and complete LCAs in the 1980s and 1990s (EMPA 1984), the LCA family now consists of several approaches to assessing environmental impacts at multiple levels. The most widely used and well-developed methodology is the bottom-up or process-based LCA, mainly developed by the Society of Environmental Toxicology and Chemistry (SETAC) and the life cycle initiative unit of UNEP (the United Nations Environment Programme) in the early 2000s. The method is based on a detailed inventory of input and output flows of processes across the life cycle stages of products or services, then converting the overall flow balance into several environmental impact categories, and then possibly even aggregating the impacts into a single score. Guidelines for performing such an analysis were further formalized in the ISO 14040-49 standards (ISO 14044, 2006).

As the need emerged for higher-level analysis of environmental impacts of entire sectors or economies, it was clear that such a bottom-up approach was unworkable for tens or hundreds of thousands of processes and products. Top-down approaches such as environmental input-output LCA and hybrid LCA were therefore developed (Hendrickson et al. 2006; Suh et al. 2004), based on taking country-level data of economic flows between sectors, and combining that with sectoral environmental data to obtain approximations of the life-cycle environmental impacts for different activities. More recently, hybrid LCA is also used at the supply chain and firm levels to enable faster assessment and identification of hot spots.

LCA methodology and tools are increasingly having practical impact, influencing policy decisions (Guinée et al. 2011, The Grenelle Law 2009) and adopted by business-focused entities such as The Sustainability Consortium (Golden et al. 2011), the Good Guide (O'Rourke 2015), and the Sustainable Apparel Coalition's Materials Sustainability Index (Angeles 2014).

The carbon footprint of a product or entity refers to the overall greenhouse gas (GHG) emissions of that system measured in CO_2-equivalent based on GWP impact category calculations. Carbon footprinting has rapidly attracted interest in industry and academia (Finkbeiner 2009), though there are various definitions of carbon footprinting (Wiedmann and Minx 2008).

With the increasing interest in measuring and sometimes reporting carbon footprints, and based on positive feedback from industry (Gawel and Rich 2008), several carbon footprinting standards have been developed, including the series of GHG Protocols by WBCSD/WRI , the PAS 2050 by the British Standards Institute for products, and the ISO 14064 standard. There are three main types of carbon footprint, each with different scope and corresponding variations in method. The *product level carbon footprint* (WRI and WBCSD 2011b; Jensen 2012) is focused on the life cycle of an individual product. The *corporate carbon footprint* (WRI and WBCSD 2004) refers to the aggregate GHG emissions of a firm, including all of its activities. In the GHG Protocol these emissions are referred to as Scope 1 (direct emissions, mostly due to on-site combustion) and Scope 2 (indirect emissions due to power consumption), and this is the footprint that firms are accountable for under the EU Emissions Trading Scheme and similar programs. The *value chain carbon footprint* (WRI and WBCSD 2011a) includes the firm's extended supply chain, known as Scope 3 in the GHG Protocol.

The product level carbon footprint is often regarded as a special case of LCA, limited to the GWP impact category (Weidema et al. 2008, Finkbeiner 2009) and excluding all other environmental impacts. Whether or not product carbon footprinting is sufficiently different in scope from LCA, and therefore merits separate standards, is a point of debate in Jensen (2012). Firms today often seem inclined to start with carbon footprinting, before perhaps moving to a more comprehensive LCA, gradually extending their focus from Scope 1 and Scope 2 to Scope 3, while learning how to collect and organize data on their activities and their supply chain performance. Past work in carbon footprinting in the academic literature mainly came from industrial ecology, often concentrating on methodological issues, and focusing on either product-level or economy-level analyses (for example, Matthews et al. 2008; Hertwich 2005; Browne et al. 2005; Acquaye et al. 2011).

Same Supply Chain, Different Models

Seuring (2004) already draws several comparisons between life-cycle management (LCM) and SCM. Among others, he comments that the typical time-frame involved in LCM is driven by the product life cycle, and hence typically in the order of months to years, while that in supply chain management can vary from hours (for deliveries) to years (for developing supply chains). He also notes that LCM focuses on material flows, while SCM also considers information flows.

With the benefit of over a decade of additional literature in LCA and SCM since Seuring's (2004) comparison, we offer a more in-depth review of seven ways in which the models used (explicitly or implicitly) in the LCA and SCM literatures tend to differ. Of course not every article in LCA or in SCM necessarily makes the assumptions we associate with that particular literature. Several of the parallels we explore here between SCM and LCA also apply to other subfields of industrial ecology; in this article, we focus on LCA for the sake of simplicity and consistency. We return to the broader context of industrial ecology later in the conclusions section. Table 1 summarizes the differences in modeling approaches; we discuss each in more detail below, first reviewing how the two perspectives differ and providing examples, and concluding discussion with a summary of what the two communities can learn from one another.

Table 1: Modeling approaches underlying Life-Cycle Assessment and Supply Chain Management

	Life-Cycle Assessment Perspective	***Supply Chain Management Perspective***
Objective Of Study	sustainability measurement in support of a decision	supporting implementation of a decision or decision rule
Dependent Variable	environmental impacts per functional unit	performance (cost, profit, or other) per unit time
Scope Of System Considered	broader system boundary including different life cycle stages	often limited to the stages that are immediately related to the decision
Environmental Impacts Considered	usually multi-dimensional	often single-dimensional
Impact Of Production Function	linear in volume	nonlinear, complex
Economic Structure Of Model	(implicitly) usually single-agent	multiple agents; incentives matter
Dealing With Uncertainty	confidence intervals for impacts	robustness of decision

Note: the characterizations in the table are necessarily overgeneralizations and imperfect; please see the text for a more nuanced discussion of each issue.

Objective of Study

One fundamental difference between much work in LCA and in sustainable supply chain management is its objective. At the risk of over-generalizing, work in LCA tends to be more geared towards measuring sustainability impacts and trade-offs (sometimes in support of decisions); recall that the definition of LCA in the ISO standard refers to "a compilation and evaluation". Conversely, work in supply chain management is more oriented towards making specific business decisions or implementing decision rules. (A decision would be a one-time decision, such as designing a supply chain network, while a decision rule would be the inventory policy to adopt at each warehouse in the network.) Needless to say, there is much overlap between these two objectives. Arriving at a good decision or decision rule requires adequate understanding of the system, both for policy and business strategy purposes, which in turn relies on measurement. Nevertheless, this contrast in focus leads to a number of differences in modeling approaches.

A focus on measurement can involve identifying hotspots, or characterizing how two products or systems differ and what drives those differences. Such analyses are often performed to help decision-makers choose between products, or to inform them where to allocate their improvement efforts. The decision context is however rarely framed as a quantitative decision analysis or optimization problem. The decision-maker's utility function and constraints are not made explicit; the (implicit) assumption is that the decision-maker will combine the insights from the LCA with other inputs to arrive at a decision.

An orientation towards implementation of a decision (rule) implies that the study does have an explicit decision context, such as optimizing a distribution network, choosing transportation modes, setting production plans and inventory levels, etc. The supply chain literature increasingly recognizes that those decisions are made by multiple independent actors, each with their own information and incentives and risk preferences. What that literature does relatively rarely is include explicit quantitative information from LCAs; the models are more often generalized abstract models with additional parameters for carbon costs and emissions rates.

To the extent that LCA studies do concern an explicit decision, it tends to be a discrete choice question. For instance, Björklund and Finnveden (2005) review a collection of articles that ask which waste management approach is preferred, between recycling, incineration and landfill. This is a different approach than asking what is the optimal design of a network of recycling, incineration and landfill facilities to manage a given collection of waste streams, or what is the optimal combination of mix of waste streams and network design, which would be more in line with the supply chain management mindset. Moreover, even when an LCA study appears to be oriented towards supporting a specific decision, the papers rarely include any discussion of that decision context, such as who the decision-makers were, what decision was ultimately made, and how it was implemented. The editorial by Baitz et al. (2013) also suggest that greater separation of methodology development and application would help to facilitate use of LCA in industry; they find that the primary goal of LCA work is sometimes focused too much on improved methods or science, while that of LCA application should be improved products or business.

To summarize: given that the modeling choices made by scholars of LCA and SCM are driven by the objective of their study, it is imperative that scholars understand why a particular study was done, as choices that are reasonable for one purpose may be inappropriate when the results of the study are used in a different context.

Dependent Variable

With "dependent variable", we mean the typical way in which the outcome of a study is represented. In line with the difference in objective, the dependent variable in LCA tends to be expressed in environmental impacts per functional unit, while in SCM it is more often expressed in performance (such as profit, cost, on-time delivery, or other) per unit time. That decision exists within an organizational and competitive context, which typically changes over time; for instance, companies can merge or vertically integrate, new logistics providers may enter the market, etc. As a result, the relevant impacts associated with a given functional unit may also vary over time. We consider two examples, related to deliberate overproduction and to allocation of fixed impacts.

Deliberate overproduction is widespread. Consider the case of Sport Obermeyer, a manufacturer of fashion ski jackets (Fisher and Raman 1996). The company has to determine production quantities for next season's styles well in advance, and the production lead time is so long that if a particular style is a hit with consumers, it is too late to make more. The opportunity cost of under-producing is high relative to the loss incurred from end-of-season markdowns of over-production, so it is optimal for Sport Obermeyer to produce more than the expected demand for each style. Fisher and Raman (1996, Table I, p. 97) determine that out of a total production of approximately 125,000 jackets (of many different styles and sizes) for the 1992/1993 season, 22,000 will have to be marked down. This represents approximately 1.3% of sales for the 1992/1993 season, and because profits are about 3% of sales, the cost of overproduction per season is 43% of profits. The performance of the production decision is evaluated per season (i.e., per unit time), rather than per jacket.

In allocating environmental impacts to individual jackets, should these 22,000 units of deliberate over-production be treated as a by-product of the 103,000 units of expected demand, or are they equivalent? There is no easy answer to this question, and when we posed this question to scholars in the industrial ecology community we have heard both views. The over-produced jackets are physically indistinguishable, so if impacts are allocated by volume or weight, they will be treated equally. They are sold at a much lower price, so if impacts are allocated by final retail value, their impacts are substantially lower. This illustrates that the impacts of a jacket can vary substantially depending on whether one defines the functional unit as "one ski jacket sold at full price" vs. "one ski jacket produced". Hypothetically, if one were able to eliminate the need for overproduction, would that change the per-unit impacts of the 103,000 units of "regular" production, or would it not affect those and only eliminate the impacts of the 22,000 units of avoided by-product? Some scholars from both disciplines are starting to touch on issues such as the environmental impact of overproduction (for example Raz et al. 2013), but there is still much to be done. From an environmental perspective, reducing over-production should be desirable, but whether or not that is reflected in the allocated burdens depends on how one answers questions such as these.

For another example of how the decision context may affect the functional unit, consider the following simple thought experiment, based on an analogy from managerial cost accounting. A firm currently charters a weekly flight to carry its high-tech products from the manufacturing plant in China to a distribution center in the US. In calculating the carbon footprint of that product, the firm takes the total emissions of the airplane per flight divided by the number of products (by volume, mass or value) on each flight. One product manager who accounts for 10% of the total volume of products realizes she can work with her customers and suppliers to get better advance demand information, allowing her to ship products by sea rather than by air. She does so, hence reducing the carbon footprint of her product, but the emissions of the flight hardly change, and are now allocated to only 90% of the products relative to before, increasing the per-unit carbon footprint for the remaining products. That prompts the next product manager to also find a way to ship by sea instead of air, further reducing the number of products over which to allocate the fixed emissions; etc.

As Anex and Lifset (2014) also point out, this is a classic problem in accounting: the financial (cost) information needed to support specific and forward-looking managerial decision-making is quite different from the financial information firms need to report retrospectively on their aggregate performance. This has to do with the problem of allocating fixed costs, which bedevils LCA and carbon footprinting as much as it does accounting. In accounting, this is addressed by using activity-based costing (ABC), which recognizes that which costs are fixed vs. variable varies depending on the specific decision context. Some authors have proposed incorporating activity-based thinking into LCA (Emblemsvåg and Bras 1999; Tsai et al. 2012), but this approach does not appear to be as widespread as it could be.

A similar distinction is that between attributional and consequential LCA (Guinée et al. 2011). Attributional LCA is comparable to financial reporting, in that it usually aims to provide retrospective and aggregate information. Most carbon footprinting takes that perspective too. For instance, in reporting the environmental impacts of milk or seafood or desktop computers, it is typically an average impact over multiple variations of the product (or the impact of one specific version which is then considered a proxy for the other variants), and averaged over a period of one or more years. For some purposes this is fine, but in a decision-making context, the allocations inherent in this attributional approach can cause distortions leading to suboptimal decisions. Consequential LCA is closer in spirit to activity-based costing, seeking to distinguish between what remains constant and what changes as the result of the specific decision being considered, but consequential LCA also faces challenges. An SCM study would ideally avoid allocating impacts or costs to individual units, and instead would focus on the system's overall performance (environmental and economic) over time rather than per unit.

To summarize: users of LCA studies need to be aware that a functional unit cannot be isolated from its decision context. Even if a well-executed LCA reports that a given functional unit corresponds to a certain inventory of impacts, one cannot assume that that inventory is meaningful when making decisions, especially business-related ones. Analogous to the statement "different costs for different purposes" in the managerial accounting field, we also need "different impacts for different purposes".

Scope of System Considered

Any study of sustainability in supply chains has to have a scope defining what is (and is not) included. Setting an appropriate system boundary is challenging, and related to the previous point: what is a reasonable scope should depend on the goal of the study and on the decision context. By and large, the scope of LCA studies is environmentally driven, while that in SCM is economically driven. "Environmentally driven" indicates that all impacts that make a meaningful contribution to the total should be included. “Economically driven”, by contrast, implies including all factors that make a meaningful contribution to overall costs or profits.

For instance, in comparing glass jars vs. plastic pots for baby food packaging, Humbert et al. (2009, p. 97) exclude capital equipment as the associated impacts do not reach their 1% cutoff level. Such a cutoff is natural if the environmental impacts are the only relevant metrics. In most business decision contexts, the economic impacts are (at least as) important. A manager choosing between glass jars and plastic pots will definitely want to include the respective costs of capital equipment, and because those costs are substantial, that manager may struggle to integrate an LCA that excludes capital equipment with an economic analysis that does include it.

Conversely, if the scope is determined by the decision context, factors which are invariant under the options being considered will often be neglected. Humbert et al. (2009, p. 97) exclude baby food raw ingredient production, as it is the same for both packaging options. This helps to focus on those aspects of the systems that drive the differences between them, but it also risks overstating the significance of those resulting differences. For instance, if the impacts of the product inside the packaging are orders of magnitude larger than those of the packaging options, does packaging really make a difference? In their comparison of three tuna packaging systems, Poovarodom et al. (2012) do include the impacts of the tuna meat itself (partly because the content weight is slightly different between the packaging options). The resulting comparison (Figure 3, p. 254) helps to put the differences between the packaging options in perspective relative to the emissions associated with the tuna meat itself. (In this particular case, both are relevant, though the tuna meat dominates.)

The more the scope of a study is economically rather than environmentally driven, the greater the risk that the resulting differences between options under consideration are essentially irrelevant. In other words, if a study focuses on a stage of the life cycle that is relevant from an economic perspective, that stage might be negligible compared to another stage when using the environmental perspective. For example, there is a substantial literature in sustainable SCM specifically on closed-loop supply chains, often based on the assumption that remanufacturing is desirable, and comparing various take-back options. However, as Quariguasi Frota Neto et al. (2010) point out, that emphasis on take-back makes sense for computers and mobile phones, where the manufacturing stage accounts for the bulk of the environmental impacts, but much less so for refrigerators and televisions, where the use phase easily dominates.

To summarize: there are both environmental and economic factors to consider when defining the boundaries of a study. To help ensure that work in LCA and SCM focuses on impacts that are meaningful, we suggest that analysts should consider the union of the scope that would result from the environmental and economic perspectives. I.e., processes that are environmentally negligible but economically significant, or vice versa, should be explicitly included within the scope. When impacts or costs are negligible and information on them is hard to obtain, they can be estimated or even set to zero. This will facilitate greater consistency between LCA and supply chain studies, and hence allow work in both fields to build more on each other more easily.

Environmental Impacts Considered

LCA recognizes a range of environmental impacts, such as climate change, ozone layer depletion, acidification, eutrophication, human toxicity, eco-toxicity, depletion of energy carriers, depletion of material resources, land use impacts, and water use impacts (Guinée and Heijungs 2016). While some LCA studies may focus on a subset of impacts, depending on the context, the default is to be comprehensive, and authors would have to defend why certain impact categories are omitted. By contrast, research in SCM often only considers a single impact, typically energy or greenhouse gas emissions. Some recent work, discussed below, is more comprehensive, and we should also point out that one stream of SCM research relies on stylized models, where the operational and economic aspects of the supply chain are also simplified.

In many cases, fossil cumulative energy demand (CED) is highly correlated with most impact categories, making it an adequate screening indicator for environmental impact comparisons (Huijbregts et al. 2006). In such cases, carbon footprinting, which the corresponding ISO standard defines as being based on LCA using the single impact category of climate change, may be an appropriate method. However, examples where insights based on CED do not carry over to other impact metrics are also well-known. Davis and Sonesson (2008, p. 580) find that for two types of prepared chicken meals in Sweden, the consumer transport component of the GWP is in the order of 15-20% of the total, while for ozone creation potential (p. 581) it is a substantially smaller portion. In other words, using CED as a proxy for ozone creation potential in this case may not be appropriate.

More disturbingly, the choice of LCA software tool and their underlying databases and process modeling can also lead to diverging insights for different metrics. Speck et al. (2015) used several tools, including SimaPro and GaBi, to compare a range of beverage packaging container types. With all tools, glass bottles cause the highest CO_2-eqv emissions and aseptic carton the lowest, though the relative ranking of the other three options (aluminum can, PET bottle, PLA bottle) varies by tool. For water depletion/consumption, the reversals are more severe: aluminum cans have the highest water consumption using GaBi but the lowest using SimaPro, while aseptic carton has the highest impact in SimaPro and the second lowest in GaBi. Speck et al. (2016) examine the impact of software in more detail and find that this divergence is caused by differences in characterization factors used.

To summarize: although energy may sometimes be a reasonable proxy for a broader range of environmental impacts, studies especially in sustainable supply chains need to recognize that there are other impact categories, and that policies that minimize one may not be preferred for others. While the recent focus on carbon footprinting in SCM is welcome, it carries the risk of obscuring other impacts, which are sometimes more important and which do not always behave the same way as GHG emissions. It is impossible for every study to consider every impact category, but at a minimum studies should be specific about the impact categories considered and avoid referring to generic "environmental impacts".

Impact Production Function

Studies in LCA typically assume (usually implicitly) that impacts are proportional to quantity of functional unit. I.e., twice as many functional units will need twice as many inputs and cause impacts that are twice as high. Supply chains are however vastly more complex, leading to highly nonlinear impacts, which can be convex as well as concave. Such nonlinearities can result in many ways. We give examples of the following:

- congestion effects;
- batching;
- safety stocks;
- the "bullwhip effect".

In *congested systems*, increasing capacity utilization from 90% to 95% will cause a dramatic increase in lead times and inventory levels, in turn precipitating a major increase in defects and product returns, far more than the 5% increase in utilization might suggest. Van Woensel et al. (2001) use queueing theory to show that congestion in traffic causes emissions that are far higher than those typically assumed in existing emissions models. Their Figure 5 (p. 213) illustrates how the effect on CO emissions of traffic density reducing speed from 40 to 30km/hr is far greater than that of going from 70 to 60km/hr.

Many activities in supply chains occur in *batches*, causing impacts to follow a step function in quantity. Trucking and shipping are obvious examples of such batch-driven discrete impacts, but others include the chemicals needed to clean a process between batches of different products, the energy and materials consumed while a process is switching from one type of product to another, etc. Changes in distribution strategy or product mix can therefore have nonlinear effects on the corresponding environmental impacts. Sonesson and Berlin (2003) use a LCA-based scenario analysis to compare several possible future structures of the milk supply chain in Sweden, allowing for various product mixes, types of packaging, recycling rates, delivery methods from stores to homes, etc. They note (p. 264): “The increasing demand for more products and for fresher products, which results in more frequent deliveries and more shopping, affects the environmental impact of several parts of the milk supply chain. Within dairies, more products and more frequent deliveries to retailers probably result in less efficient dairies.” Modeling the impact of changes in factors such as dairy operations, product mix or shipment patterns on efficiency is precisely what the supply chain management literature does well, and the effects of those kinds of changes are often non-trivial and can be highly nonlinear. Back to Poovarodom et al.’s (2012) comparison of tuna packaging systems, sterilization accounts for major differences between the carbon footprint of metal cans, retort pouches and retort cups (Figure 5, p. 255). Much of that dispersion is due to the different batch sizes used for each packaging system. A further complication of batching is that it can affect different impact categories differently. Eco-toxicity from solvents may result from changeovers, while GWP might depend mostly on transport. A firm might currently make a single product, and ship half a truckload at a time. Now it adds a new product, requiring solvents to clean the equipment during the changeover, but allowing full truckload shipments. Adding this new product causes eco-toxicity per unit to go up, while GWP per unit decreases.

Safety stocks are excess inventory held as a hedge against uncertainty in demand. If expected demand doubles, safety stock usually does not increase proportionally. As a very rough rule of thumb, if demand doubles, safety stock only increases by a factor √2 or 41%. A similar effect results from consolidating safety stock held in multiple locations in a single warehouse: 900 units of safety stock equally divided among 9 locations can be replaced by 300 units in a central warehouse (under certain assumptions on the demand distribution), even though total product flow is unchanged. Redesigning a product so that a single version can satisfy multiple markets works similarly. Excess inventory may cause impacts due to warehousing and refrigeration, or, in the case of perishables, due to obsolescence. Estimates have suggested that 20-30% of some chemicals are never used, due to poor inventory management; the benefits of chemical management services (Reiskin et al. 2000) include reducing the safety stock needed, which depends in a nonlinear way on volume.

Supply chains are often subject to the so-called "*bullwhip effect*": small fluctuations in downstream demand can cause large swings further upstream, due to a combination of fixed costs, incomplete information sharing, and conflicting incentives (Lee et al. 1997; Disney and Lambrecht 2007). The bullwhip effect is present whenever there is uncertainty and a delay in responding, which is true in most supply chains. Plambeck (2012) notes that the bullwhip effect has "dramatic implications for energy use and greenhouse gas emissions". It can cause excessive inventories in supply chains, with the impacts mentioned above. Alternatively, the bullwhip effect can cause shortages, inviting rush orders, air shipments, overtime, and contributing to congestion in manufacturing and distribution facilities. All this contributes to temporary excess emissions that could be avoided if the bullwhip effect were absent. Chen and Lee (2012) show how this bullwhip effect can be masked when looking at aggregate data, even by changing from weekly to monthly data. Because LCAs typically use highly aggregate (eg. annual) data, they are likely to miss the nonlinear increase (or reduction) in impacts that can result from seemingly small changes. A policy-maker introducing a temporary campaign promoting LED lighting or PV panels may bring about disruptions in the supply chain, making the incremental impacts due to the additional units sold as a result of the campaign far greater than those of "regular" units of the same product. These effects can distort the interpretation of LCA results in different ways. If an LCA is constructed using a process-based approach, then the deviations from the norm that result from the bullwhip effect will likely be omitted, which means they are not appropriately accounted for. Conversely, if the LCA is constructed based on aggregate data that does include the temporary excess impacts due to the bullwhip effect, then the estimated impacts per functional unit will overstate the impacts associated with a functional unit during “normal” operations.

To summarize: users of LCA studies need to recognize that the nonlinear structure of supply chains means that averages are misleading, and that the linear models used to construct the life cycle inventory (LCI) limits the range within which the findings apply. Ideally, studies in LCA would include these nonlinear effects (where relevant). Alternatively, they should clearly define the settings under which the impacts were determined – in particular, the baseline volume – and recognize that the impact inventory is only locally accurate around those settings.

Economic Structure of Model

Supply chains virtually always involve many actors. Studies in LCA may recognize the existence of those actors, but rarely explicitly take into account that they will each behave according to the incentives they face. Some recent work in the IE community is addressing this topic using complexity and agent-based modeling methods (such as that by Axtell et al. 2002; Batten 2009). For instance, a vertically-integrated firm faces a different set of incentives to reduce impacts than does a more multi-tier supply chain. The field of SCM has increasingly recognized the substantial effects that incentives can have, drawing on models from economics and game theory. We highlight two ways in which incorporating such incentives can reverse views implicitly held in the LCA community. First, if decisions related to product reuse or disposal, and the corresponding business model, are endogenous rather than assumed given, conclusions about which option is environmentally preferred may be reversed. Second, allocation of impacts gives rise to new challenges when that allocation has economic consequences.

Starting with the issue of what decisions are endogenous: there is a stream of literature arguing for the environmental benefits of service-based business models such as leasing or servicizing, both in the IE community (eg. Reiskin et al. 2000) and in the SCM literature (eg. Corbett and DeCroix 2001). The underlying argument is that if the producer retains ownership of a product, it will have greater incentive to either design the product for reuse or to dispose of it in a more beneficial manner. However, as Thomas (2003) points out, reuse in the form of second-hand sales does not necessarily reduce the sales of new goods, and can in fact increase overall material consumption. In their comparison of leasing vs. selling, Agrawal et al. (2012)

make the firm's reuse and disposition decision endogenous, in contrast to the usual case in LCA where reuse rates and disposition behaviors are considered given. They distinguish between the impacts associated with the production, use and disposal phase, and find that more remarketing of used products and designing products to be more durable need not be environmentally beneficial. Agrawal and Bellos (2016) develop this line of analysis further and allow the firm to choose between business models based on simply selling the product, servicizing, or a hybrid form, and again find that servicizing is not always the environmentally preferred business model.

Using similar arguments, modularity in product design has often been touted as an environmentally superior approach. However, Agrawal et al. (2015) point out a range of issues related to demand, technology, and competition, that are often neglected when making such assertions, and Agrawal and Ülkü (2013) indeed show that, once a firm's product development and market introduction decisions are endogenized, modular design need not always be environmentally better.

These examples illustrate how adding the economic perspective to questions raised in the LCA literature, while still recognizing the breakdown of environmental impacts in a manner consistent with LCA, can lead to richer insights for both the LCA and SCM literatures. This is also a key feature of consequential LCA, as illustrated by Rajagopal (2013), who uses equilibrium models combined with LCA to highlight possible effects of such economic factors in designing biofuel policies.

Turning to the issue of allocation: one area where incentives become particularly salient is in dealing with joint responsibility for impacts. Many impacts are the outcome of processes that are influenced jointly by two or more parties. A logistics firm may reduce emissions by using more fuel-efficient trucks or shipping more by rail or sea; the shipper can also reduce impacts by trimming packaging weight and by better planning, which reduces the need for speed. In the LCA literature, "joint responsibility" is usually taken to refer to consumers and producers having shared responsibility for an impact (Lenzen et al. 2007), but the principle is the same. When confronted with joint responsibility, most LCA and carbon footprinting literature is devoted to finding ways to allocate the impacts in a way that is "fair" and such that the allocated impacts add up to precisely the original total impact. In many contexts, this is clearly important. When estimating a total footprint, double-counting should be avoided.

The economic perspective would argue differently. There, the question is not “how do we allocate emissions in such a way that the total adds up to 100%?”, but “how do we allocate emissions in such a way that all parties have the right incentives?”. Depending on the nature of the joint responsibility, the extent to which efforts by the contributing parties can be observed and contracted on, and the nature of the agreements and contracts that the parties can credibly commit to, it is often not possible to find an allocation that adds up to 100% and that gives each firm the right incentive to reduce emissions. In the context of encouraging suppliers and buyers to cooperate to reduce consumption of chemicals, Corbett and DeCroix (2001) show that it is usually not possible to achieve the socially optimal effort levels with contracts that are linear in volume.

This is a well-known principle in economics (Holmstrom 1982). In the context of reducing carbon footprints in general supply chains, Caro et al. (2013) use this to argue that, in some contexts, double-counting of emissions is desirable. Consider a simple example: suppose that a buyer and supplier can jointly reduce GHG emissions by switching from solvent- to water-based paints, but both firms will incur costs from doing so. The socially optimal investments are derived from the benefits of the emissions reduction resulting from the buyer’s and the supplier’s efforts and the total costs of those efforts. An increase in one firm’s effort leads to an increase in benefits, but also makes the other firm’s efforts more valuable. If each firm optimizes separately, and is allocated 50% of the emissions reduction achieved, both firms will invest less than the social optimum because they do not take into account the effect of their effort on the value of the other firm’s effort. Double-counting, or allocating 100% of the emissions reduction to each firm, reverts the individual firms’ optimization problems to the socially optimal one.

To summarize: in order to predict environmental impacts of a product system or supply chain, it is essential to recognize the economic forces at play. Assuming that business model-related decisions such as reuse rates or disposition options are exogenous can lead to erroneous conclusions regarding end-of-use options. Similarly, to understand the physical breakdown of impacts, it is essential to avoid double-counting, but when setting incentives, double-counting or over-allocation of impacts may be necessary. More generally, in LCA studies, it may sometimes be beneficial to not only report the total impacts, but also the breakdown of which impacts are “seen” by key agents in the system, and which decisions those key agents make, recognizing that the components of that breakdown will likely add up to (much) more than 100%.

Dealing with Uncertainty and Accuracy of the Results

In LCA, it is well-understood that there are many sources of uncertainty. Methods such as Monte Carlo simulation are increasingly used to quantify that uncertainty, as illustrated in the comparison of hand-drying systems in Gregory et al. (2013). However, when the study aims to support a specific decision, a hypothesis-testing framework is more appropriate, as Henriksson et al. (2015) argue. Gregory et al. (2013) demonstrate that the high-speed hands-in (HSIH) system has the lowest GWP, even when accounting for uncertainty as they do in Figure 2 (p. 1614). However, if the choice is between a hands-under (HU) dryer and paper towels, the result is less clear. Figure 1 (p. 1612) shows that the aggregate GWP is comparable between the two, but the sources of impacts are quite different. Figure 2 suggests that the uncertainty associated with HU is greater, but what is really needed is a histogram of the difference in GWP between the two. Put differently, what is needed is a hypothesis test, as presented in Figure 4, which shows that paper towels have greater GWP than the hands-under dryer in 35% of scenarios, which is not a statistically significant difference.

This level of analysis, while desirable, will be beyond most firms in practical situations. Even without formally considering uncertainty, conducting a full-blown LCA for each product or process, or every time a company needs to make a decision, is impractical. Carbon footprinting as a sub-tool within LCA has been developed with more industry input from the beginning, and hence is somewhat more cognizant of practical limitations, but a full product-level or corporate-level carbon footprint for every significant decision is equally impossible. Input-output methods (Hendrickson et al. 2006), hybrid LCA (Suh et al. 2004), streamlined LCA (Hochschorner and Finnveden 2003), hotspotting (Pelton and Smith 2015), and portfolio-level footprinting (Meinrenken et al. 2012) are some of the responses that have come from the industrial ecology community to address the need for more quick-and-dirty estimates. Data collection may be expedited by integrating environmental impacts within firms' existing software systems, such as internal accounting systems, ERP (enterprise resource planning) systems, or product design software (Melville and Whisnant 2014), as exploited successfully by Meinrenken et al. (2014). However, extracting environmental impact information from financial systems carries the risk of violating the maxim of "different footprints for different purposes", discussed earlier.

In the context of supply chain management, the results of an LCA only need to be "good enough" for the decision in question. Some of the studies cited earlier do simplify or neglect impacts that are likely to be highly similar across the options being considered, which again highlights that the functional unit cannot be completely divorced from the decision context. "Good enough" to support a management or policy decision is a different hurdle than the scientific notion of accuracy underpinning much work in industrial ecology. Managers choosing between two types of packaging may genuinely want to minimize environmental impacts, but they will also ask questions such as "what if we make the wrong choice? How will we even know? What is the worst that can happen?" Or, "even if this option has lower impacts, will consumers believe it?" Instead of a confidence interval for the impacts, they will want a confidence interval for the decision.

The scientific approach to ensuring accuracy and dealing with uncertainty relies on peer review. Analogous (but more informal) mechanisms exist in business, where decisions have to withstand scrutiny from a range of executives, who may be less concerned about scientific accuracy and more about the business implications of the decision they are about to make.

To summarize: while it is important to recognize and model uncertainty in LCA studies, the analyst should remember that the "uncertainty" faced by the decision-maker may be quite different from the scientific notion of uncertainty. To avoid spending large amounts of effort on parts of an LCA that will not impact the final decision, it is important to understand the decision-maker's perspective, and to know when the results are "good enough". The results of a LCA should also be analyzed and presented in the context of the decision uncertainty, rather than in the context of the functional unit chosen for the study.

Conclusions

To recap the main premise underlying this article: there are so many similarities between the worldviews held by the LCA and the SCM communities that it is only natural for them to seek inspiration from one another. The domain of carbon footprinting is one instance of where that is beginning to occur. We chose to focus on LCA rather than on Industrial Ecology more broadly, as LCA is a more well-defined and homogeneous field (Matthews and Lifset, 2007). However, to a certain extent, the issues we raise here may apply to life cycle thinking and IE more broadly. Several of the other subfields of IE already contain elements from both the LCA and SCM side of the distinction we have drawn here.

For instance, in Industrial Symbiosis (IS), where firms find ways to exchange wastes and emissions as raw materials between them (Chertow 2000), organizational boundaries, agents involved, and economic structure inevitably come into play. Material Flow Analysis (MFA), which identifies all the sources, stocks and sinks of certain substances or materials in a life cycle perspective and how they flow within socio-technical systems (Brunner and Rechberger 2004), often takes more macro-economic factors into account. Similarly, in the view of life cycle thinking, Product End-of-life Management, where end-of-life alternatives such as reuse and recycling and their associated environmental impacts are considered, directly relates to reverse logistics and closed-loop supply chains, which have a clear focus on specific decisions. Therefore, the fact that several subfields of IE already display partial overlap with the SCM perspective makes Industrial Ecology the natural breeding ground for such closer interaction between LCA and SCM.

Our objective in highlighting where the perspectives offered by the two fields diverge is to encourage more such interaction. It is the many similarities which should make such interaction relatively easy. By contrast, it is in the differences where the opportunities lie. We hope that closer interaction between the two areas will help increase the practical impact of the work done by the LCA community, while simultaneously grounding the sustainable SCM field in a better understanding of the true environmental impacts of operational decisions.

One way to start thinking about such interaction is for scholars in each field to look at questions using the perspective provided by the other side. For example, while the starting point in OM usually is to monetize the environmental impact, to integrate it within an economic optimization framework (such as minimizing cost or maximizing profit), OM scholars should think beyond economic optimization and also consider IE perspectives. On the other side, where the IE approach mainly seeks to minimize environmental impacts, such an approach could use the help of OM with structuring optimization models that minimize the environmental impact (or that maximize the reduction of environmental impacts) of business activities and decisions and see the economic implications of that. An extended approach to optimization can also include the second life cycle of a product in case it is remanufactured and resold, meaning even further expanding the borders of the examined system.

Another avenue for further integration between industrial ecology and supply chain management is to start exploring topics beyond LCA. Much of the work in sustainable OM revolves around remanufacturing or supply chain carbon footprinting. Other areas of overlap between IE and SCM would include optimizing industrial symbiosis activities (as explored by Lee (2012)) or integrating material flows into supply chain thinking.

How does such interaction happen in practice? We hope that scholars in the sustainable supply chain field will increasingly attend conferences in industrial ecology, such as the biannual ISIE (International Society for Industrial Ecology) meeting, and that, similarly, scholars in LCA with an interest in the business context of their work will participate in meetings in the SCM community (such as the Production and Operations Management Society (POMS), the Manufacturing and Service Operations Management (MSOM) section within INFORMS, and others). Similarly, we encourage more supply chain management scholars to read (and publish in) journals such as the *Journal of Industrial Ecology*, and vice versa. The early signs provided by the recent work that is touching on some of the topics and questions we raised here are promising, though all the usual institutional challenges inherent in academia will require a conscious effort for this emerging collaboration to continue to grow.

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