SAP White Paper
Life-Cycle Assessment

MAKING LIFE-CYCLE ASSESSMENT PRACTICAL FOR BUSINESS

GETTING USEFUL RESULTS WITH THE LEAST COST, TIME, AND EFFORT

THE BEST-RUN BUSINESSES RUN SAP™

CONTENT

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EXECUTIVE SUMMARY

HOW LCA CAN HELP BUSINESSES MANAGE ENVIRONMENTAL CONCERNS

By combining the best aspects of the two main methods used for LCA – input-output and process-based methods – it is possible for businesses to minimize the time and money needed to gather data and perform assessments.

Business interest in supply chain risk management, sustainability reporting, and ecolabeling is being driven by several factors, both within and outside the business world. Perhaps the only thing that can be said for certain is that in a time of increasing energy (and carbon) prices and rising environmental awareness, these issues are unlikely to go away soon. If a company wishes to retain a good environmental image with consumers, investors, and high-quality potential employees, it must continue learning about these issues and methods of handling them while striving for continuous improvement.

One such method is life-cycle assessment (LCA), a scientific approach designed for comprehensive "cradle-to-grave" assessments of the energy use and environmental impacts of products and services. This is an important tool for businesses to understand and manage their greenhouse gas emissions.

In this paper, we outline the current state of LCA methodology and discuss its potential to help businesses become more environmentally sustainable. In its current state, LCA takes considerable effort in both up-front learning and data gathering and processing, though several tools have been developed to attempt to make the process faster and cheaper. Our main focus is on how LCA can be made as practical as possible for business. We argue that by combining the best aspects of the two main methods used for LCA – input-output and process-based methods – it is possible for businesses to minimize the time and money needed to gather data and perform assessments. Critically, we argue that the level of precision and effort should be dictated by the specific use a business has for the results.

This focus on practicality will in turn lead to more time for interpreting the results of LCAs. This will help businesses to make the necessary changes to process and product design to decrease their supply chain costs and risks, maintain good relationships with their suppliers and retailers, build brand value, and attract young talent.

INTRODUCTION
LIFE-CYCLE ASSESSMENT AND BUSINESS

Since the early 1970s, with the passage of laws restricting environmental emissions, regulation and consumer-investor awareness have made businesses more conscious of their environmental impacts. With growing global focus on energy and environmental issues, particularly climate change, the international business community is seeking tools to better understand and quantify its environmental impacts and to publicize efforts to reduce these impacts. Further, increasing energy costs, changing consumer preferences, and climate change policies[1] are driving businesses to broaden their viewpoints to include not just impacts taking place at their facilities but impacts embedded in their supply chain and in the use and disposal of their products. A key method for performing such analysis is termed life-cycle assessment (LCA), sometimes known as "carbon footprinting" of products or entities.[2]

LCA is a scientific method designed for comprehensive "cradle-to-grave" assessments of the energy use and environmental impacts of products and services. The method has roots in economics, environmental engineering, and supply chain optimization. LCA was originated to answer relatively simple comparative questions such as, which is the better environmental choice for grocery shopping bags – paper or plastic? Despite these modest beginnings, the method has now developed into its own discipline, bringing together engineers, scientists, and social scientists from several traditional disciplines. A quickly growing number of environmental consultancies specifically focus on performing LCA, and several software and database tools are available to help with its use.

Business interest in LCA originally stemmed mainly from an understanding of supply chain vulnerabilities and complexities, and this remains an important reason why businesses are interested in LCA. However, with growing public awareness and concern over environmental issues, LCA has grown in importance to many businesses for such reasons as being able to make comparative environmental claims for a company's products and avoiding scrutiny and potential embarrassment from the campaigns of environmental NGOs. Specifically, increasing business interest in LCA is being driven by three broad classes of concerns:

- Supply chain risk management (internal usage)
- Insight and decision support for product or process design (internal usage)
- Retailer or investor requirements, such as carbon labeling and sustainability reporting (external usage)

First, LCA allows businesses to understand supply chain vulnerabilities, such as the risks of higher energy costs or increased regulation of an environmental contaminant. It can also allow businesses to benchmark their energy usage or environmental progress against industry standards and support environmentally preferable purchasing decisions. In a slightly broader context, LCA can support decision making about the design of products, which includes not just supply chain vulnerabilities but also the use and disposal of the products, both of which are important factors in how consumers judge the sustainability of a product or brand.

More recently, the use of LCA has become more important from an external as well as an internal perspective. Announcements from several major retailers that energy or environmental data will be required from suppliers in the near future has led to perhaps the most compelling reason for this interest – businesses must report in order to secure future shelf space in leading retail stores. Additional external uses of such data, such as for sustainability reporting and climate disclosure to mandatory or voluntary greenhouse gas (GHG) registries, are also driving interest in LCA.

Different internal and external usages of LCA will require businesses to gather different types of data and ensure different levels of precision. For example, simply determining where the most important parts of a product's life cycle are for design planning requires much less precision than presenting that life-cycle GHG emission data in a label on the product, where it may be subject to legal or consumer challenge. Moreover, different types of products may have

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[1] These are discussed in a previous SAP white paper: Weber; C.L.; Vogel; A.; and Matthews, H.S.; Climate Change: *Challenges and Opportunities for Business* (2008).

[2] The term "carbon footprint" is used widely but as yet has no formal definition, and we thus refer to all methods for estimating greenhouse gases in products or the supply chains of entities as LCA.

different specific needs as well. For example, some products have energy use and emissions associated with their usage (appliances, autos, electronics); others don't (household furnishings, food and beverages, plastics). Services clearly constitute different challenges than physical products, and product-service systems, such as the leasing of products, are different still. Food products require detailing non-energy-related GHG emissions, such as N_2O or methane, which may not be as important for other products.

Despite the substantial information that it can offer, the use of LCA in the business world has been held back by concerns over the substantial time and resources that typical LCAs require. Because LCA studies are comprehensive in scope, they require massive amounts of data from a business's own facilities and from its suppliers. This data collection requires large amounts of staff time in addition to consultants' fees. Standards that describe the methods of LCA, such as the International Standards Organization 14040 series or the PAS 2050 standard from the British Standards Institute and Carbon Trust, specify when more general data types can be used; however, these standards remain inscrutable and difficult to navigate for many nonexperts. This has led to efforts to simplify or "streamline" the process of LCA through alternate methods, different data sources, and various simplifications.

This review focuses on the current state of the LCA field and how LCA might be made more practical from a business vantage point, given the various goals and needs businesses have for LCA. A background section introduces the concepts of LCA, especially how life cycles vary between different business and product types. We then discuss the methods currently available and the practical limitations of these methods. Finally, we examine how the various goals a business may have for LCA relate to the different methods and data sources available, and we conclude with a hypothetical case study.

Despite the substantial information that it can offer, the use of LCA in the business world has been held back by concerns over the substantial time and resources that typical LCAs require.

BACKGROUND

UNDERSTANDING PRODUCT AND SERVICE LIFE CYCLES

General Insights by Product Class

Before discussing detailed methods and data for LCA, we first introduce the concept of product[3] life cycles and the differences in product classes. There are several phases that define the life cycle of a good or service, and different products will have different shares of impacts in these various phases. Figure 1 shows a typical definition of a product life cycle, consisting of five stages: raw material extraction, material processing, manufacturing, usage, and end of life (waste management). The stages proceed linearly but have several potential feedback loops at end of life, which are recycling (where waste returns to material processing), remanufacturing (to manufacture), or reuse (to use). We add in another dimension that is not typically included in the scope of LCA: the relation of all phases to product design. Product design informs which materials end up in the product, how the product is used, and what happens to it at its end of life, while process design informs the way the product is made and thus the emissions associated with the production phase.

We will focus here on one well-known dimension of environmental impact, GHG emissions, though all the concepts can be generalized to other environmental impacts, specifically discussed later in the section "Methods for Life-Cycle Assessment." In terms of GHG emissions, products can have impacts in very different stages of their life cycles. Figure 2 shows a schematic of different industry types and where their direct impacts on climate change tend to occur. The figure orders sectors roughly from bottom to top, from primary sectors (those involved near the beginning of supply chains) to secondary sectors (manufacturing) and service sectors. In general, secondary and service sectors require output from the more GHG-intensive primary sectors at some point in their supply chains, and thus all the sectors are linked through supply chain interactions (also known as "indirect" emissions of manufacturers or service providers).

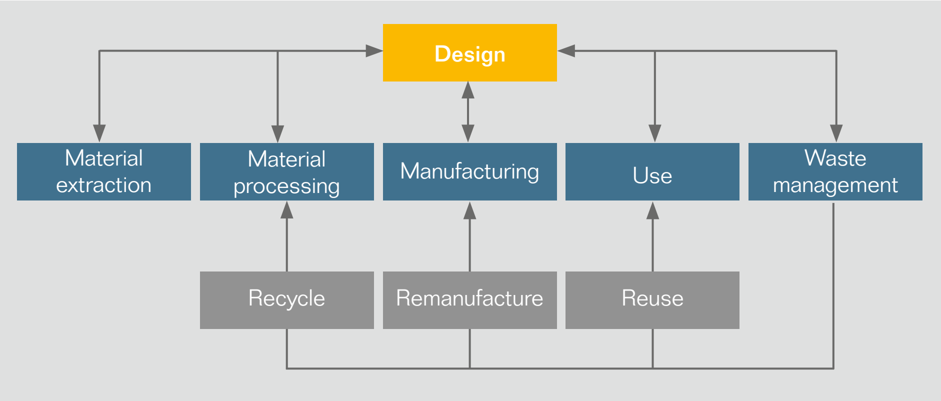

Figure 1: Phases of a Product Life Cycle and Linkages Between Phases

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[3] Here we use the term "product" to denote a physical good, service, or product-service system.

As is evident in Figure 2, primary sectors such as mining have impacts in the raw material phase, though for oil and gas, another raw material sector, impacts tend to dominate in the production phase (refining) and the use phase (the combustion of gasoline, diesel, and so on). Agriculture can be considered a raw material, and some agricultural products are used directly (fruits, vegetables, nuts) while other products (corn and soy) tend to be further processed into other food products (processed food, meat and dairy products), such that their impacts occur more in production phases. Most consumer products have their direct impacts in the production and end-of-life phases, though a special case is energy-using products such as appliances, transportation equipment, and electronics, which have substantial use-phase impacts. Logistics occur throughout all the life-cycle phases and have impacts that are usually allocated to the product that is being moved or stored. Service sectors, which produce an intangible product, have little to no end-of-life impacts but can emit greenhouse gases in the production and usage phases.

It is important to remember that the different industry groups do not exist in isolation. Consumer products, for instance, require output from the mining and chemicals sectors (such as metals and plastics) to manufacture components and final goods (as in Figure 2). Services, though they tend to be thought of as relatively low impact compared to the “dirty” energy-intensive industries like chemicals, raw materials, and so on, require products such as computers and equipment, which in turn require chemicals and raw materials in their supply chains. Thus, as these relatively energy-intensive sectors are the most exposed to potential cost increases from climate-change policy, no supply chain is free from risk due to the ubiquitous usage of raw materials to make products and services.

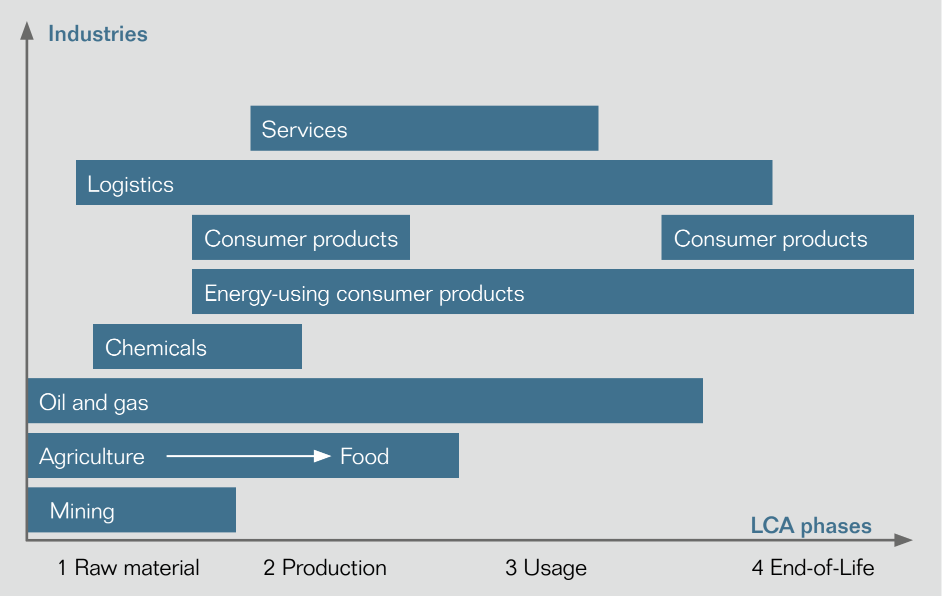


Figure 2: Schematic of Life-Cycle Stages and Industry Groups’ Impact Profiles

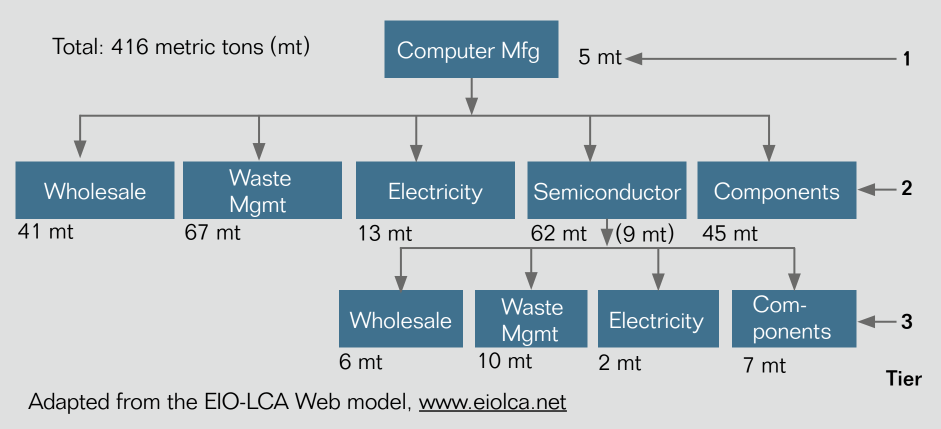
LCA and Footprinting: Considering the Whole Supply Chain

Delineating these supply chain interactions between businesses that produce final goods and those producing intermediate goods is at the core of life-cycle assessment. These interactions are what make LCA different from other tools such as entity-level tools and initiatives, notably the Greenhouse Gas Protocol, which is the most widely used standard for calculating a company's GHG emissions, and the Carbon Disclosure Project, an investor-led initiative requesting emissions data from large companies. These initiatives separate emissions into three tiers, or scopes, but only require reporting of the first two tiers, direct emissions and emissions from purchased energy. The third tier includes emissions from the company's value chain, use and disposal of its products, and all other emissions associated with an entity.

By requiring businesses to report only emissions in the first two scopes, such tools miss a large portion of the GHG emissions in the production of a good, estimated previously at around 74% for an average sector of the U.S. economy.[4] While analyses of direct emissions alone can be helpful for some of the goals businesses might have for environmental analysis (such as compliance with mandatory emissions reporting), they are far from ideal for such uses as supply chain risk management and labeling. The reasons why can perhaps best be explained through examples.

Figures 3 and 4 show some example numbers for "cradle-to-gate" (that is, raw material extraction through production but excluding use and end of life) emissions of US$1 million worth of product from various industries in the 2002 U.S. economy, in two different formats. The method used to obtain these average results is discussed in the section "Methods for Life-Cycle Assessment." Figure 3 shows a breakdown of emissions from computer manufacturing, which emits 416 metric tons (mt) of carbon dioxide equivalent (CO_2e) GHG emissions per $1 million of computers produced. Emissions are represented at each node of the supply chain, with the top of the tree (the first tier) representing final assembly, the second tier representing suppliers to the assembly facility, and the third tier representing the suppliers to the suppliers. Of course, the schematic only shows a fraction of the inputs to make a computer, and thus the nodes do not add up to the total.

The "direct" emissions from making the computer, occurring directly at the facility that assembles the computer, represent only 5 mt of the 416 mt total. Adding in the emissions from the electricity use at the assembly facility yields only 18 mt (5 mt direct + 13 mt electricity) of the 416 mt CO_2e in the supply chain. Thus, the "carbon footprint" of the computer assembler yields a very small fraction of the total cradle-to-gate life-cycle emissions. Perhaps more surprising, the total emissions associated with the top five



Adapted from the EIO-LCA Web model, www.eiolca.net

Figure 3: Industry LCA Results for the Production of US$1 Million of Computers in 2002

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[4] See Matthews, H. S.; Hendrickson, C. T.; and Weber, C. L.; "The Importance of Carbon Footprint Estimation Boundaries," *Environmental Science and Technology* (2008), 42, pp. 5,839–5,842; and Weber, C. L.; Matthews, H. S.; and Vogel, A.; SAP white paper, *Climate Change: Challenges and Opportunities for Business* (2008).

contributors to computers' supply chain emissions (wholesale trade [62 mt], waste management [67 mt], electricity [13 mt], semiconductor manufacturing [62 mt, of which 9 mt is direct], and other components [45 mt]) add up to only 249 mt of the 416 mt CO_2e of GHG emissions associated with making computers. This shows how a complex supply chain such as computer production can have large shares of emissions occurring in many small contributing supply chain components.

Figure 4 shows an alternate view, giving the fraction of life-cycle emissions for five product types (computers, coal, steel, legal services, and apparel) occurring at various supply chain tiers, this time including all suppliers at that tier. The differences between coal mining, where around 80% of the total cradle-to-gate emissions occur in the first tier of the supply chain (directly at the coal mine), and more advanced products like apparel, legal services, and computers are striking. For example, the first-tier (direct) percentage of total emissions varies from around 1% for computers to around 5% for apparel, 40% for steel, and 80% for coal mining. As a product gets more advanced and has a longer overall supply chain, the supply chain depth necessary to capture 90% of life-cycle emissions increases: it takes only two tiers to capture 90% of coal mining's GHG emissions, but three tiers for steel, four for apparel, five for legal services, and six for computers.

All these examples show the importance of examining the entire supply chain in the calculation of cradle-to-gate GHG emissions for products or industries. Even coal mining, an industry very close to raw material extraction, has more than 20% of its emissions outside of the "scope one and two" boundary required for reporting. This is true for almost any product or industry; therefore, a company trying to measure its exposure to price increases due to climate legislation needs LCA methods to truly understand its risks.

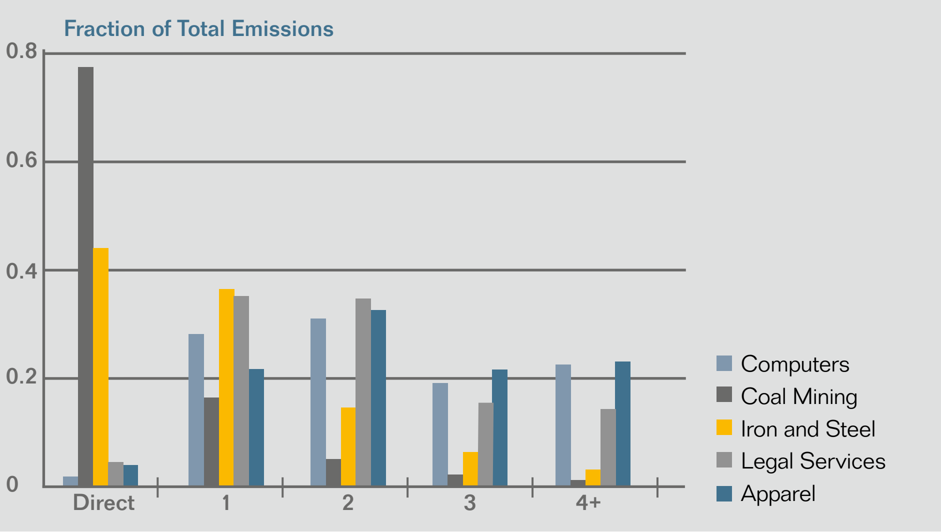

Figure 4: Percentage of Cumulative Life-Cycle GHG Emissions at the Direct and Supply Chain Tiers

Usage and End of Life: Adding Predictive Phases

The results shown in Figure 4 are general and intuitive; more complicated products have more complicated supply chains and thus more complicated life-cycle emissions profiles. However, until now we have only quantitatively discussed the raw materials and production phases. A full LCA also needs to capture use and disposal phases, which may or may not be important to businesses conducting LCA, depending on their goals and the type of product they make.

> Given the relative strengths and weaknesses of both methods for LCA, a combination of the best attributes of both would theoretically achieve the best LCA results, in terms of producing the most accurate results at least cost.

As compared to raw material acquisition and production, which are in general historic and will yield increased precision by increased scrutiny of supply chains, usage and end of life are predictive of the future use and disposal of a company's products. In other words, emissions occurring downstream from a company (assumed here to be the point of sale to consumers) are much harder to calculate than those occurring upstream from a company. This detail makes generating precise numbers for the total life-cycle emissions associated with a product difficult; however, with consistent metrics, comparison between products in the use phase can still be worthwhile and is common. Examples include the Energy Star program, EPA fuel economy ratings for automobiles, and many other rating schemes. Thus, for goals such as environmentally preferable purchasing, comparisons of use-phase emissions may be easier than supply chain production emissions. Further, if the product under consideration has potentially large use-phase emissions, estimation of the future emissions from this phase is crucial.

The end-of-life (EOL) phase is complicated in both absolute and comparative metrics, however. Like the usage phase, EOL in LCA depends for the most part on an assumption of how a product will be disposed of, recycled, remanufactured, or reused. In some cases, especially for remanufacturing, businesses may have good data on recovery rates for products. However, recycling becomes more difficult: Should a company get credit for making a product recyclable but without any recycled content? Or vice versa? Or only if the product contains recycled material that can be traced directly back to the company's own first-generation products? These issues are difficult and necessitate some level of practitioner judgment, which has led to criticism of LCA. In general, however, the inclusion of use and EOL phases, even if inexact, will help businesses to more fully understand the life-cycle impacts of their products and how improvements may be made.

METHODS FOR LIFE-CYCLE ASSESSMENT

BASIC AND HYBRID

Basic Methods: Process Versus Economic Input-Output

LCAs consist of two stages: the life-cycle inventory (LCI), where an inventory of different environmental impacts is created, and life-cycle impact assessment (LCIA), where the results of the inventory are normalized to common metrics and can be weighted into an aggregate environmental score. The results from the impact assessment can then be used to identify hot spots of environmental impact where more detailed study or improvements can be made to production, usage, or disposal or recycle phases of the product. After a brief discussion of different impacts that could be considered, we will focus on methods for LCI. Much of the recent interest in LCA is in dealing with only one or two impact categories (climate change or energy use) with well-known impact metrics (global warming potential and primary energy use) as compared with impact categories requiring more detailed models, like toxic releases and criteria air pollutants.

Today, inventory studies typically list dozens of resource inputs and environmental outputs. Impact assessment has traditionally included toxicity weighting, global warming potential, ozone depletion potential, and other calculations. Consider an automobile purchase, for example. Life-cycle impacts contain the following effects associated with the manufacturing of cars, usage (driving, petroleum refining, and production of tires), and disposal:

- Energy: estimated fuel consumption associated with production and use phase
- Climate change: greenhouse gases (CO_2, CH_4, N_2O, and CFCs) emitted during the production and use phases
- Emissions of conventional pollutants: SO_2, CO, NO_X, VOCs, lead, particulate matter, and so forth
- Toxic releases: toxic materials released by the supply chain during production
- Waste regulated by the Resource Conservation and Recovery Act: hazardous waste generated, managed, and shipped during production
- Water use: estimated amount of water used for production in each sector of the supply chain
- Land use: estimated land needed for production of all inputs across the supply chain

> The method and data used to perform the LCA should take the minimum time and money for data gathering and calculation to achieve the needed level of precision.

Process LCA

A number of institutions worldwide have been developing LCA approaches and databases since the early 1990s. In the United States, the Society for Environmental Toxicology and Chemistry and the Environmental Protection Agency have spearheaded the development efforts, publishing standards on both LCI and LCIA phases. The International Standards Organization has produced and subsequently modified standards for both LCI and LCIA as well. Other groups, including the British Standards Institute in conjunction with the Carbon Trust, the World Resources Institute, and the World Business Council for Sustainable Development, have published or are working on GHG-specific standards for businesses or products. These LCA standards are based on process models that identify and quantify resource inputs and environmental outputs at each life-cycle stage based on mass-balance calculations. This approach requires collection of detailed data directly from companies or studies published in literature. It is often termed “process LCA.”

Economic Input-Output–Based LCA

A complementary approach to process LCA uses economic input-output models to capture the upstream supply chain of results, though use and disposal phases are not included. Economic input-output LCA (EIO-LCA, also known as environmental input-output analysis, or EIOA) uses economic input-output data derived from publicly available economic and environmental data to arrive at comprehensive, industry-wide environmental impacts. The economic models behind this method, called input-output models, are developed by most countries' statistical agencies every few years (with two to five years being typical). The input-output model, at an economic sector level, is combined with energy and environmental data for the sector to describe the entire supply chain to make a good or service in economic and environmental terms. The method can only determine impacts from raw materials up to the manufacturing stage, and thus the use and disposal phases must be treated separately. A key parameter for the method is the level of detail available in a country's input-output table, as many countries use rather aggregated sectors (such as having only one sector for the chemical industry), producing potentially large errors when modeling specific commodities (such as a specific chemical within the sector).

Strengths and Weaknesses of the Basic Methods

Many authors have described the strengths and weaknesses of the two main approaches to LCI. These are summarized in the following table. Generally, process LCI is seen to be the most appropriate method for product-level analysis due to its high level of product specificity; at least in theory, data can be gathered, allocated, and summed to fully describe a specific production system of a specific product (measured either in mass or number of units). This stands in contrast to EIO-LCI, where specificity is low in general due to aggregation of unlike products within economic sectors and a reliance on production cost as the functional unit of measurement. Allocating from industry to product is a challenge in both forms of LCI, but particularly for process LCI, and especially for company overheads, such as corporate offices, business travel, and the like.

Given its specificity, process LCI has been the focus of most international standards for LCI and "footprinting" of products. However, process LCI suffers from two major weaknesses that EIO-LCI can help overcome. The first is the aforementioned large amounts of time and money necessary to fully complete an LCI for even a single product. Perhaps worse, there are relatively few opportunities for economies of scale, since data collection and allocation for one product may or may not help in an LCI of a second product. With EIO-LCI, once a model has been completed (public data gathered for energy

Method	**Resources**	**Specificity**	**System Completeness**	**Functional Unit**
Process LCI	Depends on goal and scope; can be substantial	High; product-specific	Cutoff issues	Mass or product-level (kg, units)
Economic Input-Output LCI	Up-front resources high; once completed model, relatively small	Low; sector average production	Complete by definition	Production cost ($, €)

Table 1: Broad Strengths and Weaknesses of Basic Methods for Life-Cycle Inventory (LCI) Assessment

and GHG emissions by sector), performing an LCI takes a matter of seconds, as the online implementation of several countries' models at the well-used Web site www.eiolca.net shows.[5]

Second, process LCI suffers from "cutoff" issues related to unavailable data or processes considered too insignificant to gather data for. Because each additional process considered within the scope of the study requires additional data, at some point process LCIs cut off processes deemed to be outside of the "system boundary." The choice of system boundary is somewhat arbitrary, and several studies have estimated the errors involved with cutting off at a system boundary to be significant (>50% of total impacts for some products). EIO-LCI has the theoretical advantage of being a fully complete model, in that the supply chain extends backward to an infinite order, thus comprising impacts from all inputs to make a good, including services and capital investments,[6] both usually ignored in process LCI.

Primary data should be used for important subprocesses in a supply chain, while average or secondary data, possibly from input-output sources, should be used to complete the system for smaller, less-important subprocesses.

Hybrid Methods: Leveraging the Strengths of Both Methods

Given the relative strengths and weaknesses of both methods for LCA, a combination of the best attributes of both would theoretically achieve the best LCA results, in terms of producing the most accurate results at least cost. Many practitioners of LCA have proposed various methods for "hybrid LCA" using both methods to differing degrees. The sophistication of hybrid methods varies considerably. "Tiered" hybrid approaches, the simplest methods, simply combine the use of EIO-LCI and process LCI for the production phase and then use process LCI for the use and disposal phases. Input-output–based hybrid methods retain the structure of EIO-LCI and add in process-level data where available, often by disaggregating economic sectors into the product of interest and other products. Probably the most sophisticated method, termed "integrated hybrid LCI," connects process data and input-output data within a multiunit matrix format, retaining both the detail of all available process data in physical units and the completeness of the input-output model. While this option is methodologically the most advanced, the expertise necessary for performing such an analysis is substantial.

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[5] www.eiolca.net is compiled and implemented by the Green Design Institute at Carnegie Mellon University.

[6] With additional data on capital flows within an economy

MEETING BUSINESS NEEDS

A PRACTICAL APPROACH TO LCA

With this background in mind, we now discuss how LCA can be moved from an academic and research method to a useful, informative, and practical tool for business planning. We begin, as LCAs always begin, with the various goals businesses may have in conducting LCAs. We then consider data needs and availability to meet these different goals, since data drives both the quality and the cost of LCA studies. Finally, we examine the potential role of business software in helping businesses overcome the financial and knowledge hurdles that LCA can present.

Different Goals for LCA Studies and Their Data Requirements

Different businesses will conduct LCAs for different purposes. As discussed earlier, a few potential classes of goals are:

- Supply chain risk management (internal usage)
- Insight and decision support for product or process design (internal usage)
- Retailer or investor requirements, such as carbon labeling and sustainability reporting (external usage)

Again, a key difference between these goals is whether or not the use of the LCA data will be internal or external. This distinction has ramifications for data quality and specificity. As should be clear by this point, LCAs are data intensive, and several different types of data are often used in compiling inventories. There is an inherent trade-off between the specificity of data and the time and effort needed to achieve specific product-level precision. Here we review the potential data types a business may use in conducting an LCA for any of the goals listed above. Even focusing only on GHG emissions (other environmental impacts have similar requirements), the construction of a product-based LCI could include a number of different data types. The table below describes these types of data, including the level of specificity (the term “facility” represents any single geographic location, whether a factory, store, or farm), the units in which the data is available, and whether the data is allocated from facility to product (more on this below).

GHG emissions data can either be measured directly or be estimated through the use of energy or activity data and emissions factors for energy types or activities. For example, a facility will take data on yearly energy usage (natural gas, electricity, and so forth) and multiply by CO_2 emissions factors for natural gas boilers and for the local electricity mix. Of course, this calculation only yields emissions per facility per year, not per product. Converting between facility-level and product-level data is simple when a facility performs only one task or produces one product; however, when multiple products are produced, some form of allocation must be used to apportion the emissions to the various products, coproducts, and by-products. For example, dairy farms produce meat and leather as well as dairy products, and the impacts associated with the facility must be allocated among these products. Standards have suggested both mass and economic (price) allocation methods, as well as more complicated methods of “system expansion” allocating based on alternative production methods of coproducts. There are theoretical reasons to prefer one or the other; however, consistency and transparency are the most important characteristics of facility-to-product allocation.

Name	Level of Analysis	Units	Product or Facility
Primary facility-level data	Facility	CO_2e/yr	Facility-level or product-level
Secondary LCI data	Process or product	CO_2e/kg (usually)	Product-level (usually)
Registry-type data	Facility or group of facilities	CO_2e/yr	Facility-level
EIO-LCA (top-down)	Group of industries	CO_2e/$/yr	Supply-chain of facilities

Table 2: Data Types for Compilation of Life-Cycle Inventories

Primary data, or data gathered directly from the facility or supplier of interest, is clearly preferred where it is available, since only this data type is truly representative of the product or supply chain being studied.[7] However, clearly there should be a limit to the amount of primary data gathered for any given study, since each additional primary data point, particularly deep in a product's supply chain, increases the cost and effort involved with a study. Thus, other data types, generally referred to as secondary data, can and should be used where appropriate to limit the effort associated with a study. The key is to meet the specificity and precision required for the business goal while minimizing cost.

One potential secondary data source is previous life-cycle inventories, or secondary LCI data. Several databases exist worldwide for prior LCIs, some free and others proprietary. Theoretically, secondary LCI databases represent a clear second-best option to gathering additional primary data. However, any given LCI's usefulness to another study is limited by how representative it is of the supply chain under question. Production practices, energy efficiencies of processes, and many other parameters vary in time and space, and any prior LCI for a product or component will necessarily be somewhat different than the true result obtained from the real supply chain. How representative a prior study is of current practice depends on its age and location as well as how quickly technology and production practices change for the product or supply chain in question.

GHG registries, such as the Climate Registry in North America and various government-sponsored mandatory registries worldwide, provide facility-level data, usually in the form of direct emissions and emissions from purchased electricity. Since mandatory reporting is proceeding in both the developed and developing worlds, these registries will clearly soon be an important source of GHG emissions data. However, making use of registry data requires allocation, since in general the registries will list only emissions data per facility year, not per product per year. Thus, some additional data on the production occurring at the facility in question is necessary to use this data.

The final data type is from input-output LCA databases. Some of the existing secondary LCI databases include input-output data, while other educational tools are available online using national input-output tables.[8] Ongoing work in several countries as part of the EXIOPOL project will produce a large database of such tables and results for many countries by 2010.[9] This data is highly available and allows comparison between different countries of production; however, it exists only for aggregated sectors as opposed to specific products, and it also uses production cost as the unit of measurement for products, which is somewhat undesirable given variations of prices over time and between similar products within a category (for example, organic versus conventional apples).

Matching Needs with Methods: A Least-Cost Approach

Given the different needs and goals companies have and the different data and methods available to meet these goals, we suggest a least-cost approach to achieving satisfactory results for product or supply chain LCAs. In theory, the method and data used to perform the LCA should **take the minimum time and money for data gathering and calculation to achieve the needed level of precision**. In other words, we argue that general data should be used wherever possible to avoid costly primary data collection and, further, that scoping analysis is critical to reveal which data is important enough to warrant the extra costs of primary data collection.

The needed level of precision varies for different LCA purposes and, as stated above, depends on whether the results of the LCA are intended for internal or external eyes. We summarize how the different methods and data types might be matched with goals in Figure 5. Generally EIO-LCI, the most general and thus least-cost approach, will only be marginally applicable to most business applications without further refinement. However, for general insight into

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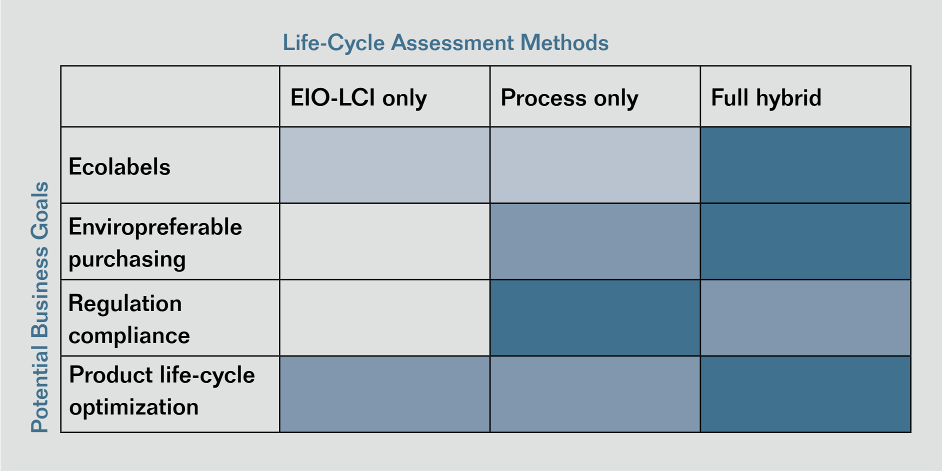
7. This is given a certain spatial and temporal context for the study. Supply chains vary over time and space, and picking this context is an important step in defining the goal and scope of a study.
8. See www.eiolca.net for such a tool, free for educational purposes.
9. See www.feem-project.net/exiopol.



Life-Cycle Assessment Methods

Potential Business Goals

	EIO-LCI only	Process only	Full hybrid
Ecolabels	░	░	▓
Enviropreferable purchasing		▒	▓
Regulation compliance		▓	▒
Product life-cycle optimization	▒	▒	▓

Figure 5: Usefulness of Different LCA Methods for Businesses' Different Potential Goals

the life cycles of products or supply chains, EIO-LCI can provide a good deal of information for a relatively small investment.

In contrast, a pure process analysis – the most detailed and thus most costly approach – will be needed for some purposes, notably compliance with regulation, where general data is of little use. Process analysis can also yield valuable insights into product life-cycle optimization and environmentally preferable purchasing when primary data is available from suppliers. However, its issues with cutoff error make it less than completely satisfactory for external uses such as making product claims via ecolabels. A complete and consistent method is needed to compare across products within a class, and system completeness can only be achieved at reasonable cost using hybrid analysis.

In general, we suggest that hybrid analysis of some type is the most useful method for most purposes a business will have for LCA. Even when it is not necessary to use primary data, as in internal product insight when liability product claims are not applicable, hybrid analysis will yield the most consistent and accurate results at a reasonable cost. Further, as hybrid analysis can yield both industry-level and product-specific results with full supply chain completeness, it is the most reliable method for comparing products, such as in carbon labeling or environmentally preferable purchasing decisions.

The more difficult question is how to combine the data types in each particular case. It seems reasonable to suggest, as many authors have, that primary data should be used for important subprocesses in a supply chain while average or secondary data, possibly from input-output sources, should be used to complete the system for smaller, less-important subprocesses. We suggest the following routine as the most practical approach to modeling a company's supply chain and approaching a full LCA:

1. **Perform a scoping analysis using EIO-LCI and simple assumptions for distribution, use, and disposal phases to get a general idea of where in the life cycle the biggest impacts exist.** Since several models already exist, this step should represent a relatively small investment for a relatively large reward in insight. To the extent that more detailed information is needed, proceed to steps 2 to 4:
2. **Gather primary data from one's own facilities and providers of purchased energy.** This data will always be important regardless of project goal, since the emissions occurring directly at a company's facilities can represent some of the easiest potential improvements in supply chain emissions.

3. **Determine where additional primary data is necessary to achieve the goal of the study.** Often this constraint can be resolved by determining whether a process constitutes a certain contribution to overall supply chain emissions, such as representing more than 1% of total emissions.
4. **After collecting primary data, recalculate supply chain emissions and assess whether the study's goals have been met.**

This approach is illustrated in Figure 6. A generic product's life-cycle emissions profile will include major contributions, represented by the larger blue arrows, and more minor contributions, represented by the small gray arrows. The first step of the approach uses a structural EIO-LCA approach for scoping which flows represent blue arrows and which represent gray arrows. Simple first-order calculations for use and disposal phases will yield an approximate size for these flows. The goal of the study (internal or external usage) will determine where the cutoff between major and minor contributions will be. Primary data should be gathered for all major contributions (blue arrows) from the business's own facilities and key suppliers, using the best available secondary process data when primary data is unavailable. For minor contributions, as well as the contributions of less-studied inputs like services, EIO-LCI data is adequate and sometimes the best available.

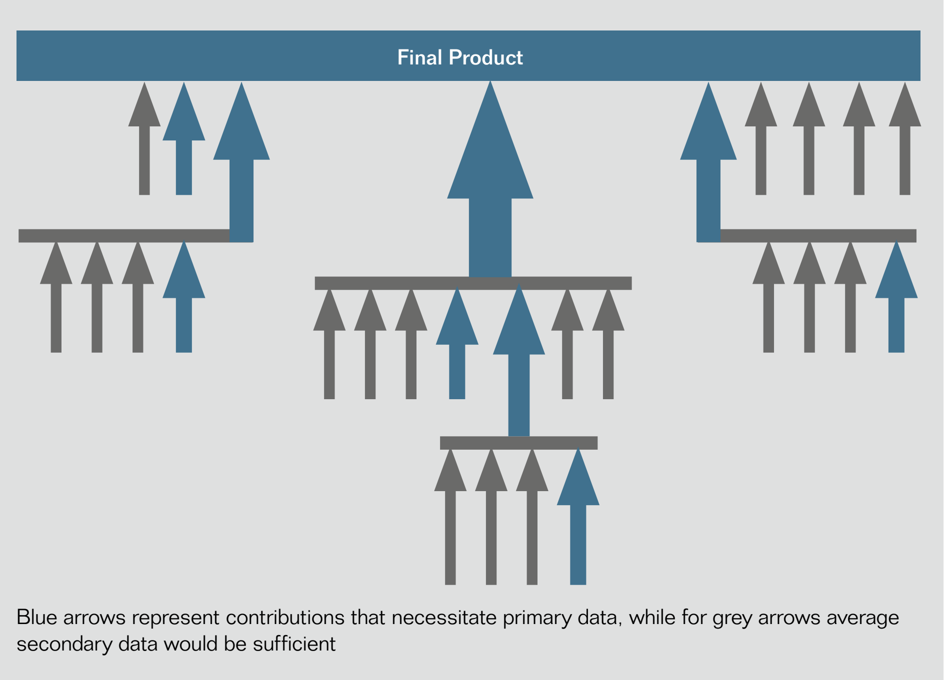


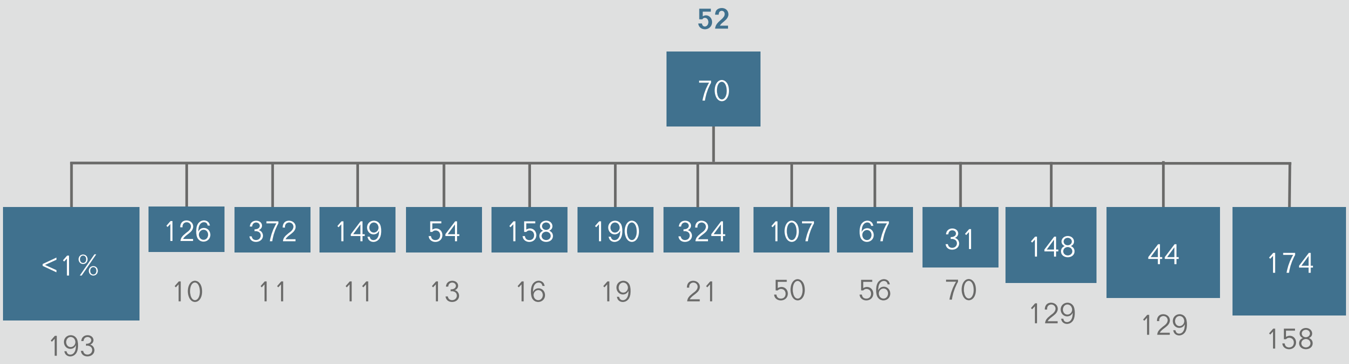
Figure 6: Practical Hybrid Life-Cycle Inventory Development

CASE STUDY
THE PRACTICAL METHOD APPLIED

We complete this review with a case study illustrating how a company in a certain sector of the economy would use this practical method to explore the carbon footprint of its products or supply chain. We use a relatively simple product – soft drinks – for illustrative purposes, while acknowledging that more complicated products will, of course, require more complex methods. A preliminary scoping assessment is performed using EIO-LCI for the production phase, combined with process data and assumptions for distribution, use, and disposal. The scoping exercise informs which data needs to be gathered in more detail using direct measurement or calculation at the facility, secondary data sets, suppliers, or GHG registries.

Upstream Supply Chain

We begin with a scoping assessment of the production phase of soft drink manufacturing. Figure 7 shows the first-tier assessment using the 2002 EIO-LCA model for some of the major impact categories involved in soft drink manufacturing.



Key	
70	Soft Drink Manuf.
174	Aluminum
44	Wet Corn Milling
148	Plastic Bottles
31	Electricity

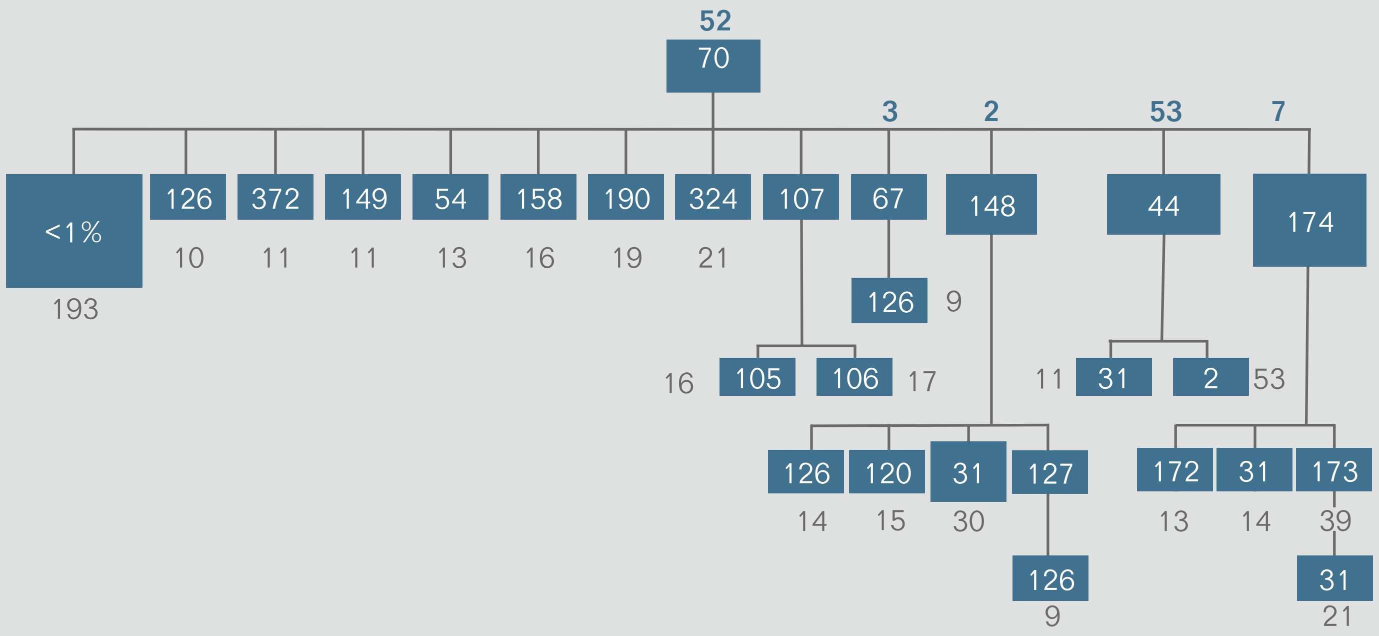
Key	
67	Syrups/Concentrates
107	Paperboard
324	Truck Transport
190	Metal Cans
158	Glass Containers

Key	
54	Fruit Processing
149	Other Plastics
372	Corporate Mgmt.
126	Organic Chemicals

Results represent the production of US$1 million (in 2002 dollars) of soft drinks produced in the United States in 2002. All numbers are in metric tons of CO_2e, with the number below representing the total supply chain beneath the node and the number above representing the direct emissions at the facility represented by the node. Supply chain nodes are numbered by sector of the economy and are shown in the key. The size of the node is roughly proportional to the sector's total supply chain emissions.

Figure 7: Scoping Life-Cycle Inventory Using EIO-LCI for Soft Drink Manufacturing

In total, to produce US$1 million worth of soft drinks, around 885 metric tons of CO_2e are produced according to the input-output model. Figure 7 shows the first-tier suppliers to the manufacturer, which represent greater than 1% of total supply chain emissions, with the remainder represented at the bottom (node "<1%", representing 193 of the 885 mt CO_2e). The supply chain GHG emissions to produce soft drinks come from a wide variety of sources, including direct energy use and emissions at the facility (52 mt of the total 885 mt CO_2e), purchased electricity by the soft drink manufacturer (80 mt), and a wide variety of supply chain purchases – the most important being syrups and sugars made from corn and fruit and packaging from aluminum, plastics, glass, and paperboard. Of course,



Key	
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107	Paperboard

Key	
324	Truck Transport
190	Metal Cans
158	Glass Containers
54	Fruit Processing
149	Other Plastics
372	Corporate Mgmt.
126	Organic Chemicals

Key	
173	Alumina Refining
2	Grain Farming
127	Plastics Resins
106	Paperboard Mills
105	Paper Mills
120	Petrochemicals
172	Secondary Aluminum

Figure 8: Detailed Scoping Analysis Including All Supply Chain Subtiers Representing More than 1% of Total Emissions in Supply Chain

logistics throughout the supply chain, such as truck transportation and wholesaling of the purchased supplies, also contribute, as well as a long list of minor contributions such as organic chemicals, corporate management (such as energy use in office buildings), and several other contributions less than 1%, including air travel, services and consultants, and various other supplies.

However, the scoping analysis should not be limited to first-tier suppliers, since suppliers further down the supply chain (suppliers of suppliers) may also represent a significant amount of emissions. Figure 8 shows a more detailed scoping analysis where all significant (defined here as >1% of supply chain emissions, but the cutoff is arbitrary, as seen below) suppliers are identified. Now it is clear that it is not as simple as gathering data from aluminum can, corn syrup, and plastic bottle suppliers, but rather that the supply chains of each of the soft drink producer's suppliers matter as well.

A total of 28 supply chain nodes lie above the 1% cutoff, representing 14 first-tier suppliers. If the soft drink maker were able to gather data for the supply chains beneath each of these 14 first-tier suppliers, it would then have primary data representing around 78% of its supply chain emissions. However, if it were only to gather site-level data (as opposed to data representing the entire supply chain upstream of the facility) even for all of the 28 supply chain facilities that lie above the 1% threshold, it would achieve primary data for only 48% of its supply chain emissions. This shows the importance of both setting the cutoff threshold low enough and including what has been called the "long tail" of supply chains, whereby the sum of small contributions leads to a large total share of emissions.

This brings up the question of effort versus completeness – how low should the cutoff be set? Twenty-eight upstream facilities would require a good deal of time and money for data gathering if all primary data was sought. To show how quickly this number can expand, the calculation was repeated using 0.1% as the cutoff. Using that 0.1% cutoff, 180 facilities are included, with still only 64% of supply chain emissions represented by direct emissions at these 180 facilities. Thus, in this case it seems that 1% may be a reasonable threshold for additional data gathering. One option would be to consult secondary data sets for well-studied supplies whose production practices do not vary much in time or space, such as aluminum production, plastic bottles, and corn syrup. The advantage of consulting secondary LCAs for such products is that the entire upstream supply chain will be included if a past study is available, and thus improved estimates of large chunks of upstream emissions may be obtained at a smaller cost than primary data gathering.

The scoping analysis shows several areas of concern for the producer's upstream supply chain. Direct energy use and electricity are clear contributors, as are the main ingredients in soft drink manufacture – syrups and sugars from corn and fruit. The various methods of packaging the product, including aluminum cans, plastic bottles, and paperboard cases, are also of clear importance. After this, the contributions get somewhat smaller in scale, though transport and logistics should clearly be of concern. Each of these major contributions – aluminum, plastics, glass, paperboard, flavoring syrups, and energy and electricity – deserve more detailed data gathering, while the remainder of the supply chain, given its small individual contributions, could be modeled as industry average.

Usage and Disposal Phases

However, the EIO-LCI method only models the supply chain through to the factory gate, and thus the distribution, use, and disposal phases must be estimated through process modeling. Though carbonated beverages likely do release some carbon dioxide while being consumed, these emissions are probably minor compared to the emissions to produce the soft drink, and thus the use phase can probably be ignored in this case. For the distribution phase, the producer would need to gather data on transportation distances and modes from their production facilities to the point of sale and, potentially, on energy use during display or retailing (such as in display cases in retail stores, in soda machines, and so forth). Shipping using both company-owned and third-party trucks should be included; at least for the company fleet, a good estimate of fuel usage is probably already available and could easily be converted to emissions with data on the carbon intensity of fuels.

Of particular importance to this case study would also be the disposal or recycling phase, as one of the biggest environmental impacts associated with soft drinks is the solid waste associated with their packaging. Data on recycling rates for the various modes of packaging would be needed, as well as data on recycled content used in the containers the producer purchases. As discussed above, recycling and end-of-life assumptions are among the more difficult issues in LCA, and how emissions are allocated between the end of life and recycled secondary materials would change the results. The most conservative way to deal with the issue would be to assume no recycling and all virgin material for all packaging materials. While this is probably close to true for plastic, aluminum and glass have nonzero recycling rates. One advantage of the granularity associated with EIO-LCI in this case is that primary and secondary (that is, recycled) metals and glass are averaged in input-output tables, and thus the numbers from EIO-LCI would reflect the average mix of virgin and recycled materials, which may be good enough for a first-tier assessment.

Lessons Learned

The scoping assessment for a soft drink producer showed several important subprocesses in the production of soft drinks – direct energy usage, purchased electricity, syrups and sugars, aluminum, plastics, glass, and paperboard. Of course, if product-level assessment was the goal of the study, this industry average would need to be split into the various delivery mechanisms for the soft drink – cans, bottles, and boxes – and the variations in production practices between different kinds of soft drinks would need to be identified. Given the mass of soft drinks, which are mostly water, the distribution phase is likely to be important as well, though it depends on the average distance traveled in distribution and the energy efficiency of the fleet moving the drinks. Finally, since a large proportion of the upstream supply chain was in the production of packaging materials (around 42% of the total), the recycling stage will clearly be important for the company, though harder to quantify in LCA.

LCA must adapt to business just as business is adapting and learning to perform LCA.

CONCLUSIONS

FINDING THE BEST METHOD FOR LIFE-CYCLE ANALYSIS

Business interest in supply chain risk management, sustainability reporting, and ecolabeling is being driven by internal and external factors. Given increasing energy (and carbon) prices and rising environmental awareness, these issues will likely grow in importance in the near term. If a company wishes to retain a good environmental image with consumers, investors, and high-quality potential employees, it will need to continue learning about these issues and methods of dealing with them while striving for continuous improvement. Life-cycle assessment provides an important tool for businesses to understand and manage their GHG emissions, as well as energy use and other impacts on the environment.

That said, LCA takes considerable effort from business. Time and effort spent on performing LCAs, gathering supplier data, and reporting to retailers, NGOs, and government is time not spent performing other vital business tasks. Thus, LCA must adapt to business just as business is adapting and learning to perform LCA. We have presented a summary of some of the main methods and issues involved in LCA for GHG accounting, with a focus on making LCA as practical as possible for business. In its current state, LCA takes considerable time and money, even when it is done at a general level. Methods vary in their specificity and involved effort, and much of the current literature discusses using the best of both main methods of LCA in hybrid analyses.

With the combination of the best of input-output and process-based methods, it is possible for businesses to begin gathering data and performing assessments without the large investments of time and money that LCAs have typically taken. More important, though, is that by combining input-output LCA scoping with primary and secondary data for important processes, businesses can begin reducing the GHG impacts of their products through better process and product design.

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