Chapter 5
Looking Beyond the Factory Gates: Life Cycle Assessment, Supply Chain Management and Design for Environment

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Abstract This chapter gives an overview of the principles of life cycle assessment (LCA), supply chain management (SCM) and design for the environment (DfE). They are all placed at Level 2 in the CapSEM Model as tools for enhancing the product by improving the actual production processes that take place at different stages and subsystems in the life cycle of a product. One way of analysing and ameliorating the environmental performance of a product can be by analysing the environmental aspects and impacts initially by performing a life cycle assessment aimed at finding the most significant environmental impacts in the life cycle of the product. These hotspots can then be identified under different suppliers in the upstream value chain. Results from this analysis should then be addressed in the design of a new product, and further result in changes to the supply chain by supply chain management. An optimal solution for improving the environmental impacts at the different stages of the life cycle of a product, can be achieved at the end by introducing this into design principles as better specification of the performance at each stage in the life cycle of the product. This chapter also introduces green public procurement as a driver for change in the supply chain.

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A. M. Fet (ed.), *Business Transitions: A Path to Sustainability*,
https://doi.org/10.1007/978-3-031-22245-0_5

5.1 Introduction

Since the introduction of cleaner production (CP) programmes in the early 1990s, the focus has gradually expanded to include activities outside factory production sites. Businesses became more aware of their responsibilities during the entire value chains of their products, both upstream and downstream. The CapSEM Model suggests tools for analysing and evaluating impacts of products and activities in a life cycle perspective along value chains. This chapter gives a general introduction to life cycle assessment tools, including the standardized Life Cycle Assessment (LCA) to consider the product system, Supply Chain Management (SCM) to manage the value chains of suppliers and products, and design for environment (DfE) to integrate environmental concerns in the development of products and services.

5.2 Life Cycle Analyses Tools

A life cycle assessment takes the entire life cycle of a product into consideration, i.e., the *cradle to grave approach* (Hauschild 2018; Owens 1996). Life cycle assessment methodologies, LCA, Life Cycle Costing (LCC), and Material Input per Service unite (MIPS), are related to products and their life cycle chains, materials, production processes, distribution, and disposal with the most comprehensive tool being the LCA (Ness et al. 2007). Performing a complete LCA for a product consisting of a high number of components, is very time-consuming. Companies may not want to perform a complete LCA, but rather want to obtain an overall impression of key environmental issues linked to the product value chain. Simplified analyses such as Life Cycle Screening (LCS) or Material, Energy and Toxicity (MET) studies may be used for this. When environmental life cycle analyses are combined with LCC-analyses, they are appropriate for decision support or strategic planning related to both product and process improvements.

5.2.1 Environmental Life Cycle Assessment

In order to consider a product's specific environmental aspects, the most extensive method available is LCA methodology. LCA methodology was first developed in Switzerland in the 1960s and further developed by the Society of Environmental Toxicology and Chemistry (SETAC). It became standardized as an international standard in 1996 and is included in the ISO 14000-family of environmental management standards (ISO 2006a, b). During the 1990s, many studies reported omissions and weaknesses within the methodology (Lindfors et al. 1995; van den Berg et al. 1995). Although the standards have been in use for many years, debate remains around the accuracy and relevance of the results of an LCA (Ross et al. 2002; Owens 1996). LCA methodology includes the steps *goal and scope definition*, *inventory analysis*, *impact assessment* and *interpretation* (ISO 2006a). These steps are still identical, but details under each step have evolved over the years and the entire process is well documented in the literature (Hauschild 2018). The direct applications of an LCA is for product development and improvement, strategic planning, marketing and public policy making.

The results of the inventory analysis comprise a list of all raw material consumption, and emissions identified in every process of the entire life cycle are known as the inventory table. This information is usually presented in process flow-charts and used by companies to present an overview of the product system and subsystems (or modules). This overview of quantitative information is further used to analyse and assess the impacts of the environmental burdens identified in the inventory analysis. There is no commonly accepted methodology for consistently and accurately associating inventory data with specific environmental impacts. It is also problematic to find weighting factors which can be adopted globally, due to environmental conditions are under changes as a result of climate changes and pollution in the ocean, for example. Nevertheless, a process impact assessment includes classification, characterization, and valuation. The main purpose of this classification is to briefly describe which potential environmental impacts are caused by the inputs and outputs. During classification, the different parameters from the inventory table are noted under the relevant impact categories. For example, all emissions contributing to global warming are noted under the heading 'Global warming'. The characterization is a quantitative step in which the relative contributions of each input and output to its assigned impact categories are assessed, and the contributions are aggregated within the impact categories. In the valuation, the relative importance of different environmental impacts are weighed against each other. Results from the valuation normally form the basis for environmental improvement priorities. During this stage, different environmental impacts can be weighed and totalled to form an environmental index. An indication is thus available on how one effect can be compared to another.

For the purpose of improving a product, this information is of importance for its design. The findings may also form recommendations to decision-makers in the supply chain.

5.2.2 Life Cycle Screening Tools

Life cycle screening tools were developed to support the development of routines for performing an LCA. When the intention is to identify key issues for further investigations, e.g., identify parts of a life cycle that needs further research, Life Cycle Screening (LCS) is recommended (Heijungs 1996). LCS is a simplification of an LCA, however it can never claim to be a substitute for a full LCA (Bovea and Pérez-Belis 2012; Suppipat et al. 2021). The name *MET matrix* is derived from the first letter of the LCS categories, i.e., Material cycle, Energy consumption and Toxic emissions (Brezet and van Hemel 1997). The MET-matrix is a tool for quickly identifying a product's main environmental aspects (Stefanov 2017). It is a simple input-output model combined with the product's life cycle. The nature and the volume of raw materials used in the product are considered, as well as the energy it requires and the waste and emissions it generates. This requires reflection on the product's entire life cycle, from the extraction of raw materials up to and including processing the product after it has been disposed. Three categories of environmental aspects are distinguished in this input-output model as follows:

- Material cycle: raw materials - materials - waste (a line that should be transformed into a cycle)
- Energy consumption: energy consumed during the various stages of the product
- Toxic emissions: hazardous emissions to water, soil, and air

Material Input Per Service unit (MIPS) is another tool developed in 1990s. The MIPS concept is a life cycle tool for analysing material inputs per service unit. It measures ecological impact, showing the same system boundaries for all examined services. Services imply utilization that could be obtained from a product (or infrastructure) to satisfy human needs and desires. In this concept, the product is conceived as the *service delivery machine*, or *service machines*, focusing on the use of resources and less on waste streams. By calculating material and energy flows and the number of products produced, the material intensity related to the function of that product can be calculated, thereby creating a picture of the environmental performance related to that product. The concept is based on the philosophy that better utilization of materials and resources is needed to achieve a sustainable development (Liedtke 1994; Robèrt et al. 2002).

A direct comparison of the MIPS between products that differ in their consistency is significant in cases of functionally equal products. The definition of the service unit is therefore important. The calculations start with a screening phase where the product's material intensity measure is calculated based on inputs alone. It is not necessary to count waste outputs, which would result in double counting, because waste is the difference between material inputs and products (or service) outputs. After the first screening, all known eco-toxicities of the material flows associated with goods or services are carefully considered. The counting of material intensity or resource productivity, the inverse of material input per service unit, 1/MIPS, is referred to as Material Intensity Analysis (MIA). With MIA it is possible to compare the ecological impact intensity of functionally equal substituents (Liedtke et al. 2014). This concept has become an integrated part of LCA as all material flows should be referenced to the functional unit of the analysed product together with its supply chain.

5.2.3 Life Cycle Costing (LCC)

Economic issues drive many decisions in industry, and the results from an LCA-study can be linked to LCC information (Asiedu and Gu 1998). Traditionally cost effectiveness implies *most performance for least cost*. LCC is a comprehensive life cycle approach especially designed for capturing economically related issues with a focus on costs and revenues - not environmental issues (Norris 2001). It involves the collection and sometime estimation of all costs associated with the activities planned and/or accomplished throughout the system life cycle. This includes the costs of research and development, design, production/construction, operation, maintenance and support, and system retirement (Blanchard 1990). Another cost examination instrument is the Value-Added Analysis (VAA), which is related to the MIPS-concept (Azapagic and Perdan 2000). VAA supports an evaluation of the marketability of an eco-efficient product. A comparison between different production technologies or substituents based on both MIA and VAA provides an estimate of where in the life cycle of products and services a low ecological impact can be reached.

5.3 Supply Chain Management

The life cycle perspective makes SCM highly relevant for addressing improvement in sustainability. Whilst SCM originally did not initially focus on sustainability, the inherent, underlying systemic similarities between SCM and LCA suggests that SCM can serve as an important driver and enabler of improving overall sustainability and further encourage the adaptation of approaches such as LCA and LCC (Blass and Corbett 2018).

5.3.1 What is Supply Chain Management?

SCM as a managerial concept emerged during the late 1980s from the field of logistics management, extending the key principles of logistics to a higher system level covering a focal firm's upstream suppliers and downstream customers. Christopher (2016) defines logistics as:

> ...the process of strategically managing the procurement, movement and storage of materials, parts and finished inventory (and the related information flows) through the organization and its marketing channels in such a way that current and future profitability are maximized through the cost-effective fulfilment of orders.

SCM can then be thought of as logistics management across multiple, serially connected actors, i.e. the supply chain. Christopher's (2016) definition of SCM is used widely:

> The management of upstream and downstream relationships with suppliers and customers to deliver superior customer value at less cost to the supply chain as a whole.

The interorganizational dimension of SCM brings with it specific challenges. Coyle et al. (2003) identify several mutually related, areas of attention in SCM, including inventory management, a concern for minimizing the final cost for the final customer, accurate and fast information exchange between upstream and downstream actors, developing relationships and forms of collaborative planning with these actors and addressing the perceived division of risks and gains. The increasing focus on circularity in supply chains further adds to the importance and complexity of addressing these areas of attention (De Angelis et al. 2018). For example, a shift towards circular supply chains is likely to change the interaction patterns, material flows and types of value exchange between various actors, including information flows, the location and types of inventories held, the need for collaboration and planning, and novel business models (along with the implications of these models for sharing risks and rewards).

5.3.2 Why is SCM Important for Sustainability?

When considering the previous section on LCA through the lens of SCM, one could argue that a *life cycle* (LC) perspective coincides with, and implies, a *supply chain* perspective. After all, assessing costs as well as environmental impacts related to the development, production, in-service and dismantling of a product will likely correspond to different stages in a supply chain, i.e., producers of components, producers designing and assembling complete products, wholesalers and distributors of products, final users and service providers. Just as the service level and cost performance offered to the final customer is the sum of the contributions of all supply chain actors involved, so is the environmental impact. Since the first decade of the 2000s, increasing attention has been paid to unravelling SCMs potential as a driver for sustainability, resulting in the body of literature known as Sustainable Supply Chain Management (SSCM), defined by Carter and Rogers (2008) as:

> … the strategic, transparent integration and achievement of an organization's social, environmental, and economic goals in the systemic coordination of key interorganizational business processes for improving the long-term economic performance of the individual company and its supply chains.

In their framework, SSCM builds on four key dimensions:

1. sustainability as an integrated aspect in overall firm strategy
2. risk management, including contingency planning and audits
3. ingraining sustainability in the firm's culture and values and
4. creating transparency, by stakeholder engagement and other measures.

LCA and related approaches clearly support several of these dimensions, most notably carrying out risk assessment and creating transparency. As part of their concept of Shared Value Creation (SVC), Porter and Kramer (2011) identify redefining the activities in the value chain as a key strategy for linking economic value creation to social and environmental value creation, pointing to logistics and purchasing as important areas of attention. Achieving SVC will typically require collaboration across upstream and downstream supply chain actors (as well as other actors in the wider ecosystem) and as Porter and Kramer (2011) indicate: '…successful collaboration will be data driven, clearly linked to defined outcomes, well connected to the goals of all stakeholders, and tracked with clear metrics.' By aligning LCA with supply chain management, a change towards green supplier selection (GSS) takes place. A strengthened focus on environmental responsibility strategies motivates a growing tendency to integrate LCA-based information. Igarashi et al. (2013) indicated how LCA plays an important role in contributing to greener supplier selection. As suggested in their analysis, the use of LCA needs to be aligned with both a focal organization's overall strategy as well as the supply chain context. The use of LCA should be considered in the various stages of the GSS.

In addition, the outcomes of assessing the alignment of the overall strategy with the supplier selection processes will probably also have consequences for how various steps in the green supplier selection process are carried out and how the supply chain context is mapped. Building further on Igarashi's work, Jenssen and De Boer (2019) more specifically identified suitable application strategies for LCA in GSS.

5.4 Design for the Environment

Alongside SCM, Design for Environment (DfE) signifies another important progeny from LCA in the transition towards sustainability. DfE has evolved as practical approach to design products and services thereby meeting environmental challenges identified in LCA.

5.4.1 Background

In 1989, the United Nations Environment Programme (UNEP) began work on approaches for preventing pollution. The resulting strategy, *Cleaner Production*, is an essential part of the Sustainable Production and Consumption Policy (Clark 2007). Since the early 1990s, producers and designers from various industries started to work with cleaner production strategies and to pay attention to the reduction of negative impacts along the life cycle of a product – from extraction of its raw materials to its ultimate disposal. Simultaneously, the Design for the Environment (DfE) approach emerged as a non-regulatory aid for companies to consider sustainability effects when designing and manufacturing commercial products and processes (Ehrenfeld and Lenox 1997). In addition to incorporating environmental concerns into product and service solutions, DfE evolved out of product life cycle assessment (DeMendonça and Baxter 2001). DfE has had an impact on different types of production and manufacturing. It has been part of the Xerox industrial design since 1990, when the company started a 5-year effort to create waste-free factories including 90% minimum reduction in solid waste to landfills, air emissions, hazardous waste, and process wastewater discharges (Azar et al. 1995). DfE has also influenced companies such as Philips and the ICT branch (Mottonen et al. 2010).

5.4.2 Methods for DfE

DfE enables designers to consider traditional design issues around cost, quality, manufacturing process and efficiency as part of a unified decision system (Zheng et al. 2019; Anderson 1995). Using DfE encourages developers to apply LCA to all potential environmental implications of a product or a service being designed, including energy and materials used, manufacture and packaging, transportation, consumer use, reuse or recycling and disposal. DfE tools enable consideration of these implications at every step of the design process (Eagan and Pferdehirt 1998; Bras 1997). The Dutch PROMISE approach (Brezet et al. 1994) is an early DfE approach, which aims to assist business in setting up systematic environmental product development. Tools such as the MET matrix and LCA are recommended in the search for the most important environmental criteria in the product life cycle. Another useful tool for monitoring DfE impacts is the Ecodesign strategy wheel, which comprises seven design strategies for environmental product development. By using a simple grading, poor – average – good, it is possible to map the performance of initial, improved and new products, and then compare their environmental performance against each other. During the 1990s, DfE and the emerging ecodesign concept consisted mainly of quantitative and empirical methods, and subsequent improvement strategies concentrated on the material and energy flows within a system of producers and consumers, aiming to build knowledge about how these flows can be fed into design processes to improve products and production routines (Keitsch 2015). DfE and ecodesign facilitate navigation through the complexity of industrial and natural ecosystems within which societies and businesses operate (Bras 1997).

Brezet and van Hemel (1997) came up with an Ecodesign Strategy Wheel, which is often referred to and in common usage. It illustrates the ways in which product development can be aligned with SCM, DfE and ecodesign. The product development process consists of the following stages: strategy, product planning, need identification, research, analysis, idea generation, concept detailing, customization, marketing. The stages are unexchangeable, however iterations are often made in idea generation, concept detailing, and at customization stages. When designing environmentally sound products, aspects of LCA, DfE and SCM should be integrated at the product planning stage and permeate the whole product development process (Fig. 5.1).

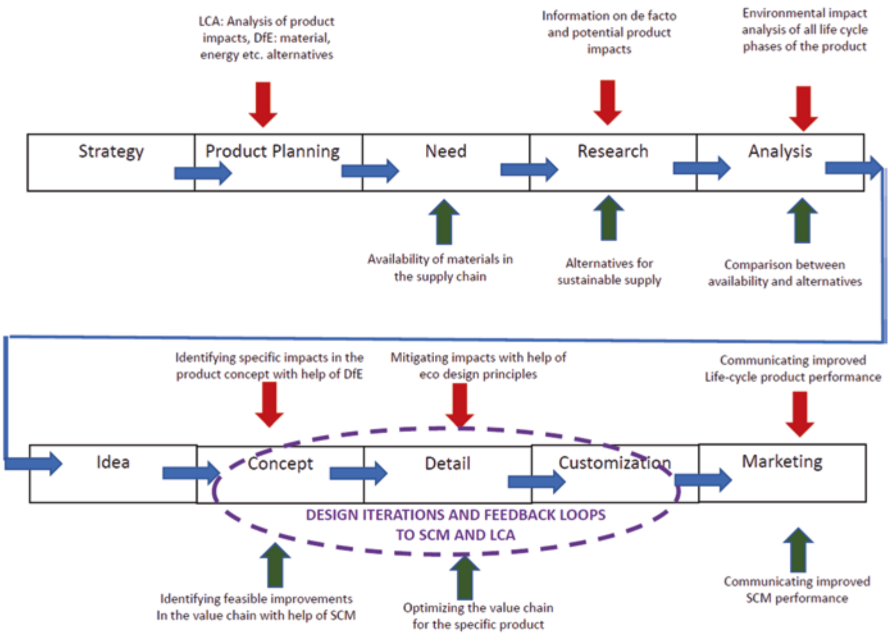

Fig. 5.1 Product development stages integrating aspects of LCA, DfE and SCM

5.5 Conclusion

LCA, SCM and DfE each have their own strengths and limitations. LCA considers environmental impacts over the life cycle of a product or a service. An LCA requires comprehensive inventory data where information should be collected throughout the value chain of the product. The popularity of outsourcing means that parts of the actual products for which the LCA is undertaken, can be produced in different locations world-wide and make it difficult to gather specific data. Some of the suppliers of such parts might be direct suppliers or sub-suppliers for the company producing the product for which the LCA is performed. Serious impacts can appear much further away in the supply chain. SCM therefore requires a significant level of stakeholder involvement when increasing an organization's awareness around sustainability. The interorganizational dimension of SCM results in both coordination and monitoring challenges. The combination of LCA and SCM is an appropriate approach to reduce environmental impacts and costs via different mechanisms to drive the production of products and services towards sustainability. Similarly, LCA is an important and helpful tool for gathering information feeding into the DfE-process. DfE and SCM both address environmental issues through design and innovation to influence companies' strategic decisions. They thus contribute to the further development of principles for integrated models for the achievement of sustainable design as a sustainable solution: either as a product, or, as a service. This has become a growing field of research across different disciplines, and a rich field for interdisciplinary collaboration.

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