A LIFE CYCLE ASSESSMENT METHODOLOGY TO SUIT THE APPAREL INDUSTRY

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DECLARATION

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Abstract

Emissions, waste generation and consumption of resources occur at different phases in a product's life cycle. This is a complex issue characterised by uncertainties and ignorance; and contributes catastrophically to effects, such as global warming, stratospheric ozone depletion, eutrophication, acidification and depletion of resources. Hence, it is important to address these product-related contributions in a more holistic and integrated manner. This research focuses on the development of a methodology to enable easy application of Life Cycle Assessment (LCA) in the apparel industry. The objectives were to study LCA methodologies, identify unique LCA parameters for the apparel sector, develop an LCA approach for the apparel industry and to evaluate it.

By analysing the existing methodologies, an LCA methodology for the apparel industry was developed. It was named as Fibre-to-Fashion LCA. The approach had six main steps to be followed sequentially, namely, goal definition, scope, data, life cycle inventory, life cycle impact assessment, and improvement analysis. These steps also included sub-steps, which intended to guide the users of this approach. It was then applied to a cotton blouse manufacturing company in Sri Lanka.

Fibre-to-fashion LCA provided a systematic and transparent approach to analysis of the environmental impact associated with the product during its entire life cycle. The simplification approaches avoided the complexities and time consuming nature of LCA, and provided veritable means of achieving objectives through a narrow domain. However, interpretation phase was hampered by the number and the heterogeneity of impact assessment results, as well as by the uncertainties arising from data, models and practitioner's choices, which are customary to the LCA approaches.

The environmental impacts due to garment manufacturing were found to be comparatively less and it is only through improvements in fibre and/or fabric performance(s) that the environmental impacts can be altered. There is a distinct limitation on the extent to which the environmental impacts can be modelled in order to map real-life scenarios and further research is needed to establish impact models that are compatible for different special boundaries.

Keywords:

Sustainability, Life cycle assessment, Life cycle inventory.

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List of Abbreviations

BOD	Biological Oxygen Demand
COD	Chemical Oxygen Demand
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
NMVOC	Non-Methane Volatile Organic Compounds
PM	Particulate Matter

Chapter 1

INTRODUCTION

The concept of Life Cycle Assessment (LCA) was conceived in the United States and the European Union in the late 1960s and 1970s as a systems approach to evaluating resources and energy use, along with the associated burdens created in air, water and land (Franklin, 1995). Until the oil crisis subsided in the early 1980s, energy use was considered a higher priority than were waste and outputs (Elcock, 2007; Jensen, Hoffman, Moller, & Schmidt, 1997).

In 1993, the Society for Environmental Toxicology and Chemistry (SETAC) published its Code of Practice, which described the components of the “traditional” LCA, i.e., goal and scope definition, inventory analysis, impact assessment, and improvement assessment (Elcock, 2007). Then, the International Organisation for Standardisation (ISO) launched the 14040 series of standards that covered LCA principles and methodologies.

LCA can assist in avoiding a narrow outlook on environmental concerns by the following: compiling an inventory of relevant energy, material inputs and environmental releases, evaluating the potential impacts associated with identified inputs and releases, and interpreting the results to help practitioners to make more informed decisions (Kalliala & Nousiainen, 1999; Nieminen, Linke, Tobler, & Beke, 2007; Ridoutt, Sanguansri, & Harper, 2011; United States Environmental Protection Agency, n.d.).

A cradle-to-grave analysis involves a “holistic" approach, bringing the environmental impacts into one consistent framework. This aids the decision maker in studying the entire product system, hence avoiding the sub-optimisation. It is important in eco-design to not solve one environmental problem merely by shifting it to another stage in the product’s life cycle. For example, LCA data can recognise the transfer of potential environmental impacts from one media to another (e.g., eliminating wastewater by creating air emissions instead), and/or from one life cycle stage to another (e.g., from production phase to the raw material acquisition phase).

If an LCA was not performed, the transfer might not be recognised and properly included in the analysis because it is outside of the typical scope or focus of the product selection processes. Secondly, when selecting between two alternatives, one option might appear better for the environment because it generates less solid waste than does the other. However, an LCA study may determine that the first option actually generates a much larger cradle-to-grave environmental impact when measured across all three media (air, water, land) (e.g., it may cause more chemical emissions during the manufacturing stage). Therefore, the second product (that produces solid waste) might be viewed as producing a lesser cradle-to-grave environmental impact than does the first alternative, due to its lower chemical emission (Azapagic, 1999; Campion et al., 2012; Frischknecht, 1998; Hauschild, Jeswiet, & Alting, 2005; Liang, Zhang, & Xu, 2012; Menoufi et al., 2012; Ministry of Housing, Spatial Planning and the Environment [VROM], 2002; Scharnhorst, Hilty, & Jolliet, 2006; Scientific Applications International Corporation [SAIC], 2006; Woolridge, Ward, Phillips, Collins, & Gandy, 2006).

Thereby, LCA assists in controlling the magnitude of pollution, conserving non-renewable resources and ecological systems, developing cleaner technologies, and maximising material recycling. However, there is still no consensus on how to monetise environmental damages in a consistent way. Conversely, the omission of social impacts from the life cycle impact assessment is also, to a certain extent, not consistent with the defined areas of protection, as social impacts may lead to impacts on human health, and indirectly, on the sustainable use of ecosystems (Hauschild et al., 2005). In addition, the application of this concept is complicated due to difficulty in data gathering, its time consuming nature and the subjectivity in certain decisions. This hinders the spread of LCA methodologies to the industry sector, especially in developing countries.

Globally, the textile industry moves towards the development of sustainable systems. Furthermore, since 2011, some global apparel fashion brands have publicly committed to achieving the goal of zero discharge of hazardous chemicals (ZDHC) by 2020. The latter is applicable across the entire supply chain. In order to achieve this goal, mechanisms for disclosure and transparency about the product system are required. In the current context, the apparel industry, the biggest export earner in Sri

Lanka, needs to be equipped with a more holistic approach to achieving sustainability. However, there is a lack of proper methodology for analysing the life cycle of a garment in Sri Lanka. Thus, identifying or developing a methodology for life cycle assessment of a garment could be important to the industry and society as a whole, as the environmental impacts, which are not addressed in the current context, as well as the opportunities for improvement, could be significant.

1.1 Aim

The aim of the research is to develop an LCA methodology for the apparel industry.

1.2 Objective

In this pursuit, the following objectives are considered.

- To study LCA methodology.
- To identify unique LCA parameters for the apparel sector.
- To develop an approach for the apparel industry.
- To evaluate the approach.

1.3 Methodology

Literature review: A literature survey was conducted to determine the extent of the LCA methodologies, as well as to assess studies on LCAs that were conducted by other researchers/practitioners. The explicit requirements and parameters inherent in the life cycle stages of a garment were also examined.

LCA approach: Considered practical scenarios and developed an LCA approach for the compilation and evaluation of potential environmental impacts in relation to apparel manufacturing.

Case study: Conducted a case study to understand the overall performance of the approach, and interpreted the findings of the study.

1.4 Structure of the Report

Chapter 1 provides introductory information about life cycle assessment and its application. The basic framework, definitions, theories and dynamic aspects of LCA in the literature are reviewed in **Chapter 2**.

The application guide is provided in **Chapter 3**, where steps that need to be followed to execute an LCA are illustrated chronologically. **Chapter 4** consists of the case study carried out based on the methodology described in the previous chapter. Finally, a discussion, conclusions and proposals for future research are provided in **Chapter 5**.

Chapter 2

LITERATURE REVIEW

This literature survey was carried out in between January 2012 to February 2014. All documents, including journal articles, government reports and other publications referred to in this report, were obtained using the Internet, and most of the journal articles were obtained through ScienceDirect. In order to focus on more recent developments in the field, the literature review was mainly confined to references produced during last 15 years. Table 2.1 illustrates the categories and amount of literature reviewed. Higher priority was given for journal articles and international standards when compiling the dissertation.

Table 2.1: Summary of literature reviewed

Area	**Category**	**Journal articles**	**Conference papers**	**Governmental reports**	**Other reports & manuals**	**International standards**	**Magazines**	**Web sites**
LCA	Theoretical	31	1	7	10	9	0	2
	Application	7	1	1	12	1	0	6
	General	2	0	1	9	0	1	8
Sustainability and LCA	Theoretical	4	0	0	0	0	0	0
	Application	6	0	0	0	0	0	0
	General	0	0	0	0	0	0	0
LCA for Textiles	Theoretical	2	0	0	0	0	0	0
	Application	3	0	0	3	0	0	0
	General	6	0	0	1	0	0	0
Summary								
All categories	**Theoretical**	**37**	**1**	**7**	**10**	**9**	**0**	**2**
	Application	**16**	**1**	**1**	**15**	**1**	**0**	**6**
	General	**8**	**0**	**1**	**10**	**0**	**1**	**8**
	Total	**61**	**2**	**9**	**35**	**10**	**1**	**16**

2.1 LCA and Basic Framework

The International Organisation for Standardisation (ISO) defined Life Cycle Assessment (LCA) as the "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO 14040, 2006a). Figure 2.1 illustrates the possible life cycle stages that can be considered in an LCA, such as development, production, use, recycling and disposal, as well as the typical inputs/outputs measured. The continuous arrows represent material and energy flows and the dotted arrows represent information flows. It is important to note that primary resources, such as energy, are used in many stages including the final disposal.

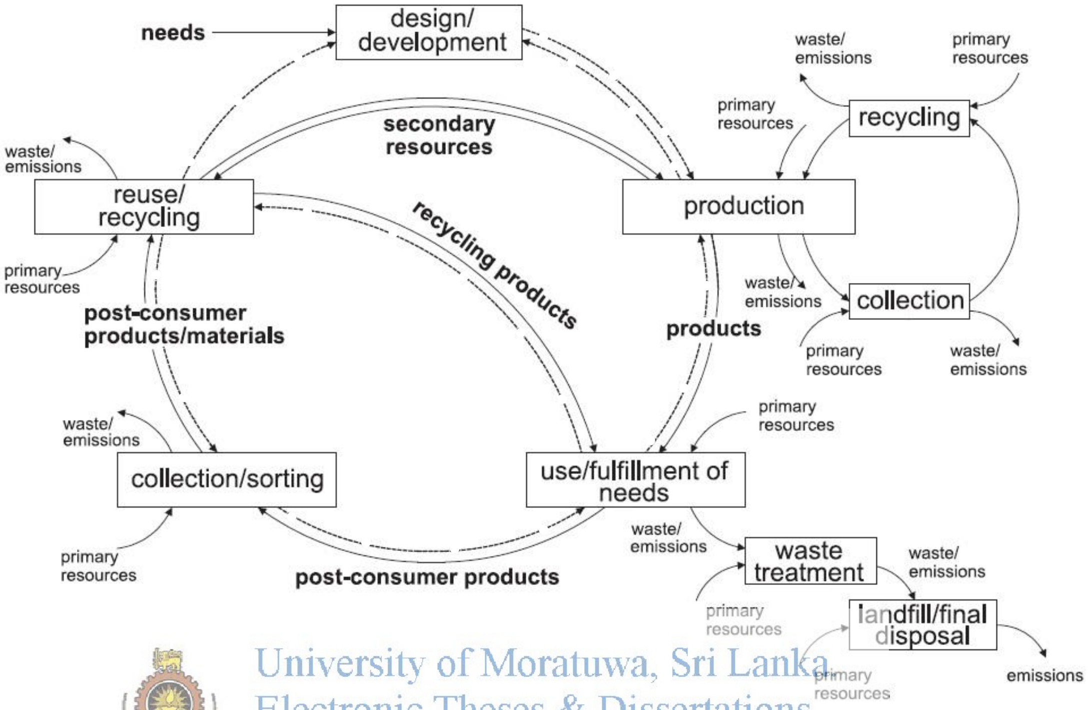


Figure 2.1: Schematic representation of the generic life cycle of a product
Source: Rebitzer et al. (2004)

LCA is, as much as possible, quantitative in character. Where this is not possible, qualitative aspects are taken into account so that as complete a picture as possible can be given of the environmental impacts involved (VROM & CML, 2001).

ISO 14040 (2006a) illustrates the four phases of LCA:

Goal definition and scoping: The scope, including the system boundaries and the level of detail of an LCA, depends on the subject and the intended use of the study. The depth and the breadth of LCA can differ considerably depending on the goal of a particular LCA.

Life Cycle Inventory (LCI): The LCI analysis is the second phase of LCA. It is an inventory of input and output data with regard to the system being studied. It involves the collection of the data necessary to meet the goals of the defined study.

Life Cycle Impact Assessment (LCIA): The purpose of an LCIA is to evaluate the potential human health and environmental impacts identified during the LCI.

Improvement Analysis (Life Cycle Interpretation): Life cycle interpretation is the final phase of the LCA procedure. During this phase, the results of an LCI or an LCIA, or both, are summarised and discussed as a basis for conclusions, recommendations and decision-making in accordance with the goal and scope definition.

2.2 International Standards on LCA

2.2.1 Society of Environmental Toxicology and Chemistry (SETAC)

SETAC was the first international body to act as an umbrella organisation for the development of LCA (Ministry of Housing, Spatial Planning and the Environment [VROM] & Centre of Environmental Science – Leiden University [CML], 2001). The SETAC LCA Advisory Group serves as a focal point to provide a broad-based forum for the identification, resolution and communication of issues regarding LCAs. In a broad sense, SETAC facilitates, coordinates and provides guidance for the development, implementation and communication of LCA and its use by publishing journals and organising conferences, such as the Annual SETAC North America Meeting (Society for Environmental Toxicology and Chemistry [SETAC], 2013).

2.2.2 International Organisation for Standardisation (ISO)

The ISO 14000 series of standards for “Environmental Management” provides a practical toolbox to assist in the implementation of actions supportive to sustainable development. The ISO 14040 standards give guidelines regarding the principles and conduct of LCA studies (ISO, 2009). The following general standards have been released by ISO in the 14040 series:

ISO 14040:1997 – Environmental management, Life cycle assessment: Principles and framework – This stipulated the practice, applications and limitations of LCA to a broad range of potential users/stakeholders. The second edition was released in 2006.

ISO 14041:1998 – Environmental management, Life cycle assessment: Goal and scope definition and inventory analysis – The standard provided special requirements and guidelines on life cycle inventory analysis during which inputs, outputs and emissions of a product system were compiled/quantified.

ISO 14042:2000 – Environmental management, Life cycle assessment: Life cycle impact assessment – This provided guidance on the impact assessment phase of LCA, which aimed at evaluating the potential environmental impacts in relation to the life cycle inventory analysis.

ISO 14043:2000 – Environmental management, Life cycle assessment: Life cycle interpretation – This provided guidelines for interpreting LCA results in relation to the goal definition phase of the LCA study, involving the review of the scope of the LCA, as well as the quality of the data compiled.

ISO 14044:2006 – Environmental management, Life cycle assessment: Requirements and guidelines – This standard replaced ISO 14041:1999, ISO 14042:2000 and ISO 14043:2000, providing an enhanced readability. It provided guidelines on inventory analysis, impact assessments, the interpretation of LCA results and data-quality.

2.2.3 United Nations Environment Programme (UNEP)

The United Nations Environment Programme (UNEP) was the third international body in the field of LCA (VROM & CML, 2001; VROM, 2002). UNEP and SETAC worked together to develop the current work *Towards a life cycle sustainability assessment*, which combined environmental life cycle assessment, life cycle costing and social life cycle assessment, which are pillars of sustainability, into an integrated assessment. It also outlined how they can be used to contribute to a life cycle sustainability assessment (LCSA) (United Nations Environment Programme [UNEP], 2011).

2.3 Environmental Management, Sustainability and LCA

LCA is one of several environmental management techniques, such as risk assessment, environmental performance evaluation and environmental auditing. However, it might not be the most appropriate technique to use in all situations (Guinee, Huppes & Heijungs, 2001; ISO 14040, 2006a; Institute of Environmental Science, 2011; VROM, 2002).

In the general context, LCA is an accepted and standardised method for evaluating environmental performance. Since sustainability assessment includes environmental performance as well as social and economic performance, interpreting and measuring those are a great challenge for practitioners. Hence, the ability of LCA to support actual decision-making in companies that aim for sustainability might be questioned (Allwood, Laursen, Russell, de Rodríguez, & Bocken, 2008; Hauschild et al., 2005; Rosen & Kishawy, 2012; Ridoutt et al., 2011). However, contemporary studies (e.g., Finkbeiner, Schau, Lehmann, & Traverso, 2010; Heinonen & Junnila, 2011; Lehmann, Russi, Bala, Finkbeiner, & Fullana-i-Palmer, 2011; Schau, Traverso, Lehmann, & Finkbeiner, 2011; UNEP, 2009) on social and socio-economic impacts provide guidelines on the basis of the most current and state-of-the-art methodological developments for assessing a product based on social and socio-economic indicators.

2.4 Variants of Life Cycle Assessment

2.4.1 Retrospective LCA vs. Prospective LCA

Tillman (2000) described two distinct categories of life cycle assessment, which are also mentioned in other literature (e.g., Ekvall, Tillman, & Molander, 2005; Finnveden et al., 2009; ISO 14040, 2006a; ISO 14044, 2006b; UNEP, 2009). Tillman (2000) and ISO 14040 (2006a) stated that retrospective or accounting perspectives deal with assigning elementary flows and potential environmental impacts to a specific product, while prospective perspectives study the environmental consequences. Tillman (2000), as cited in Ekvall, Tillman, and Molander (2005), stated the following:

> *In retrospective LCAs, the systems include the whole life cycle stages from cradle-to-grave whereas activities contributing to the environmental consequences of a change, regardless of whether these are within or outside the cradle-to-grave system of the product investigated in a prospective LCA.*
>
> *If applicable, in prospective LCAs, marginal data are used to assess the consequences and allocation problems are avoided by expanding the system boundaries to include affected processes outside the cradle-to-grave system.(p.1226)*

2.4.2 Cradle-to-Grave

A cradle-to-grave analysis involves taking a "holistic" approach where all of the stages of a product's life, from cradle-to-grave, are screened, bringing the environmental impacts into one consistent framework, and thus, avoiding a narrow outlook on environmental concerns, i.e., "problem shifting" (VROM & CML, 2001).

2.4.3 Cradle-to-Gate

A cradle-to-gate approach screens the upstream part of a product's life cycle, which includes all stages, from raw material extraction to the product at the factory gate, as its LCA model (Pirlo, 2012; Weiss & Leip, 2012).

2.4.4 Cradle-to-Cradle or Open Loop Production

Cradle-to-cradle is a specific kind of cradle-to-grave assessment, where the end-of-life disposal step for the product is a recycling process (Todd & Marry, 1999).

2.4.5 Gate-to-Gate

This is a partial LCA that looks at only one value-added process in the entire production chain. Gate-to-gate modules may also later be linked in their appropriate production chain to form a complete cradle-to-gate evaluation (ISO 14040, 2006a; Todd & Marry, 1999).

2.4.6 Well-to-Wheel

Well-to-wheel is a conceptualised framework in relation to transporting fuels and vehicles when assessing energy consumption/energy conversion efficiency and the impacts of vehicle emissions, including their carbon footprint and the fuels used. The analysis is split into different stages, such as "well-to-station", or "well-to-tank", and "station-to-wheel", "tank-to-wheel", or "plug-to-wheel". The upstream component incorporates the feedstock or fuel production, processing and fuel delivery or energy transmission, whereas the vehicle operation is analysed during the downstream stage (California Energy Commission, 2007).

2.4.7 Economic Input-Output LCA

Economic input-output LCA (EIO-LCA) involves the use of aggregate sector-level data on the degree of environmental impact attributable to each sector of the economy, as well as how much each sector purchases from the other sectors (Inoue & Katayama, 2011). EIO-LCA, in turn, assesses the emissions based on monetary transactions, which are based on the idea that every monetary transaction is related to production of a good or service that causes emissions (Heinonen & Junnila, 2011).

The principal differences with respect to process-LCAs are those of data sources (unit process data versus economic national accounts), commodity flow units (physical units versus economic value), level of process/commodity detail, and covered life cycle stages (complete life cycle vs. pre-use/consumption stages). EIO-LCA is characterised by more coarsely modelling commodities in terms of sectorial outputs and hence, the unit processes in a life cycle. Hence, the level of detail and the possible differentiation between similar products is limited. Results of EIO-LCA can be used either for screening purposes or to roughly estimate the overall environmental impacts of goods and services on a regional, national, or international level (Rebitzer et al., 2004).

2.4.8 Ecologically-based LCA

Eco-LCA quantitatively takes regulating and supporting services into account during the life cycle of economic goods and services. In this approach, services are categorised into four main groups: supporting, regulating, provisioning and cultural services (Center of Resilience, n.d; ISO 14044, 2006b).

2.4.9 Hybrid LCA

LCA, based on unit processes, is specific and detailed, while generally possessing incomplete system boundaries due to the orientation necessary for compiling the data from the product system. On the other hand, EIO-LCAs are more complete in system boundaries, but lack process specificity. A model that attempts to overcome the disadvantages while combining the advantages of both methods is generally referred to as a hybrid approach (Rebitzer et al., 2004).

This approach facilitates life cycle assessments with incomplete information, and enables the creation of models that significantly reduce the truncation error inherent in process-LCAs, while reaching to process specificity. In addition, hybrid-LCAs are well suited for assessments within the context of the built environment, where the studied systems tend to be complex in nature (Heinonen & Junnila, 2011).

The hybrid approach provides more complete system definitions while preserving process specificity with relatively small amounts of additional information and inventory data. Different methods in hybrid approaches, however, vary in level of sophistication, additional data, and resource requirements. The uncertainty is further reduced by collecting process-specific data for those inputs that are identified as key contributors in the EIO-LCA. By iterating the procedure, an LCA practitioner can achieve both higher levels of completeness and accuracy (Rebitzer et al., 2004).

2.4.10 Summary

In the general context, all LCA variants are conceptualised around one basic framework and methodology, while the application depends on the specific occasion.

These models, such as “cradle-to-grave” and “cradle-to-cradle,” have the visibility of all life cycle stages of a product, and hence, they avoid sub optimisation. This is in contrast to “gate-to-gate” (or cradle-to-gate) approaches, which have a narrow perspective. Conclusions drawn on similar approaches may not yield the best result due to this reason. The hybrid LCA model is recognised as being more practicable for real-life scenarios.

2.5 Goal Definition and Scoping

ISO 14040 (2006a) stated that the depth of detail and the timeframe of an LCA vary considerably, and to a large extent, they depend on the goal and scope definition. This definition states the intended application, reason for carrying out the study and the intended audience. The scope is sufficiently well defined in terms of temporal, geographical and technological coverage, as well as the level of the study’s sophistication in relation to its goal (VROM, 2002).

2.6 Modelling the Product System

LCA models the life cycle of a product as its product system that performs one or more defined functions. It can be considered a typical static simulation model (Rebitzer et al., 2004). The essential property of a product system is characterised by its function and cannot be defined solely in terms of the final products. The level of modelling detail that is required to satisfy the goal of the study determines the boundary of a unit process (ISO 14040, 2006a).

In a retrospective LCA, the processes included are those that are deemed to contribute significantly to the studied product and its function. In contrast, the processes in a prospective LCA are those elements that are expected to be affected on short and/or long term by the decisions that are supported by the study (Rebitzer et al., 2004).

The products that are the object of the analysis are described in terms of function, functional unit and reference flows (VROM, 2002). Figure 2.1 illustrates a simplified product system that is subdivided into a set of unit processes. These unit processes are linked to one another by flows of intermediate products and/or waste for treatment, to other product systems by product flows, and then to the environment by elementary flows. In some systems, certain inputs are used as a component of the output product, while others (ancillary inputs) are used within a unit process but are not part of the output product. A unit process also generates other outputs (elementary flows and/or products) as a result of its activities. The elementary flows include the use of resources and releases to air, water and land associated with the system (ISO 14040, 2006a).

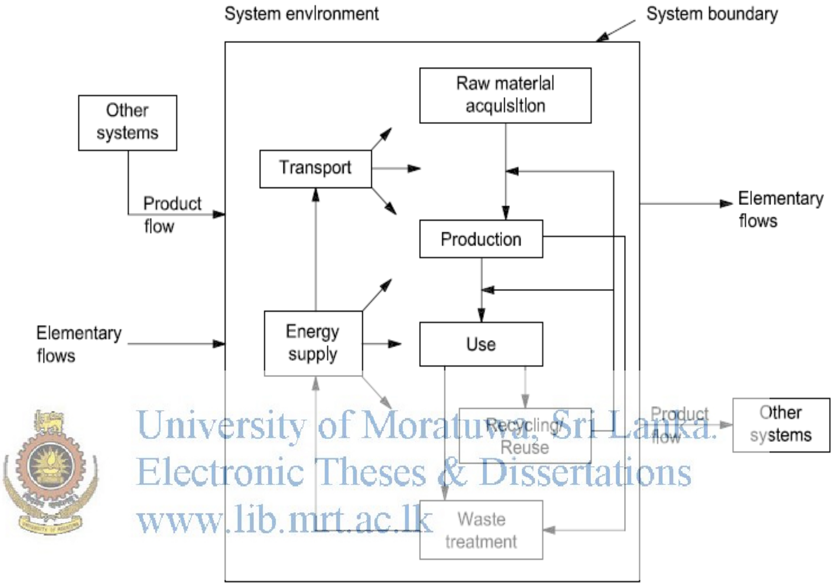


Figure 2.2: Example for a product system for LCA
Source: ISO 14040 (2006a)

2.7 Functional Unit

The functional unit quantifies the identified functions (performance characteristics) of the product. Thus, it provides a reference where the inputs and outputs are related, and consequently, the LCIA profiles are related to the functional unit. This reference is necessary to ensure comparability of LCA results when different systems are assessed (ISO 14040, 2006a).

Rebitzer et al. (2004) proposed taking a broader function-based perspective, i.e., based on the needs fulfilled by the products (e.g., ‘‘lighting’’ and ‘‘cooling of food’’) rather than based on the physical products themselves (e.g., ‘‘lamps’’ and ‘‘refrigerators’’) to avoid differences in functional output (performance of product system) and the consequent need for adjustments. In a retrospective LCI, the system is modelled linearly, and the results all scale linearly with the functional unit. The magnitude of the functional unit is not significant. In contrast, a prospective LCI is an estimate of the system-wide change in environmental effects resulting from a change in the level of the functional units produced. As the consequences do not scale linearly with the magnitude of the change, the results of a prospective LCI are easier to interpret if the functional unit reflects the magnitude of the change investigated (ISO 14040, 2006a).

2.8 Setting Up of System Boundaries

LCA deals with complex interwoven networks of industrial, agricultural, household and waste management activities. The pattern of activities is dispersed over many locations and may span decades. These activities are influenced by mechanisms of a technical, economic, social, cultural and political nature. The mathematical relationships that describe these real mechanisms in principle are non-linear, dynamic and will often show hysteresis and irreversibility. Hence, the LCA model should be able to cut out a product life cycle from the interconnected complex (Guinee, Huppes, & Heijungs, 2001). Each flow is followed until its economic inputs and outputs have all been translated into environmental interventions, i.e., flows crossing the boundary between the product system and the environment (VROM, 2002).

The system boundaries define the unit processes to be included in the system, where the choice of elements of the physical system to be modelled depends on the definition of the goal and scope of the study, as well as its intended application and audience, the assumptions made, data and cost constraints, and cut-off criteria. To create a clear distinction between the product system and the environment, as well as between elementary and other flows, the product-environment boundary needs to be explicitly defined. The decisions regarding the data to be included, in certain applications, can be determined on the basis of a sensitivity analysis to ascertain their relative significance. Therefore, the initial system boundaries are revised, as appropriate, in accordance with the cut-off criteria established in the definition of the scope (ISO 14044, 2006b; VROM, 2002).

The criteria used in setting the system boundaries are important for the degree of confidence in the results of a study, as well as the possibility of reaching its goal. When setting the system boundaries, different life cycle stages, unit processes and flows should be taken into consideration (ISO 14044, 2006b). An LCA Inventory Analysis distinguishes between three types of boundaries: the boundary between the product system and the environment system, the boundary between processes that are relevant and irrelevant to the product system (cut-off), and the boundary between the product system under consideration and other product systems (allocation) (VROM, 2002).

ISO 14044 (2006b) stated that making the initial identification of inputs based on mass contribution alone might result in important inputs being omitted from the study. Accordingly, energy and environmental significance should also be used as cut-off criteria in this process.

Baumann and Tillman (2004), as cited in Rinde (2008), indicated that the production of capital goods is rarely included in retrospective (accounting) LCA in order to keep the amount of data manageable. In addition, maintenance is normally excluded, as the impact seems to be relatively negligible. UNEP (2009) referred to the inclusion of buildings and maintenance as a matter of motivating the cut-off criteria. The inclusion should be in line with the goal and scope of the study.

2.9 Allocation

Allocation involves “partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems” (ISO 14044, 2006b). Most industrial processes are multifunctional. Their output generally comprises more than a single product, and raw material inputs often include intermediates or discarded products (VROM, 2002).

ISO 14044 (2006b) stated that as some outputs are partly co-products and partly waste, the ratio between co-products and waste needs to be established since the inputs and outputs are allocated to the co-products’ parts only. Furthermore, it emphasised that allocation procedures need to be uniformly applied to similar inputs and outputs of the system under consideration. For example, if allocation is made to usable products leaving the system, then the allocation procedure has to be similar to the allocation procedure used for such products entering the system. ISO 14044 (2006b) defined following procedure for allocation:

Step 1: Divide the unit process to be allocated into two or more sub-processes and collect the input and output data related to these sub-processes, or expand the product system to include the additional functions related to the co-products.

Step 2: Where allocation cannot be avoided, partition the inputs and outputs of the system between its different products or functions in a way that reflects the underlying physical relationships between them; i.e., they reflect the way in which the inputs and outputs are changed by quantitative changes in the products or functions delivered by the system.

Step 3: Where the physical relationship alone cannot be established or used as the basis for allocation, allocate the inputs between the products and functions in a way that reflects other relationships between them (e.g., economic value of the products.)

2.9.1 Allocation procedures for reuse and recycling

The partitioning becomes a methodological problem when reuse and recycling (as well as composting, energy recovery and other processes that are similar to reuse/recycling) imply that the inputs and outputs associated with unit processes for the extraction and processing of raw materials and final disposal of products are to be shared by more than one product system. It is also implied when reusing and recycling change the inherent properties of the materials in subsequent use (Ekvall et al., 2005; ISO 14044, 2006b; Shen, Worrell, & Patel, 2010). In order to overcome the above problem, ISO 14044 (2006b) proposed the following procedure, which is illustrated in Figure 2.3.

- A closed-loop allocation procedure applies to closed-loop product systems. It also applies to open-loop product systems where no changes occur in the inherent properties of the recycled material. In such cases, the need for allocation is avoided since the use of secondary material displaces the use of virgin (primary) materials. However, the first use of virgin materials in the applicable open-loop product systems may follow the open-loop allocation procedure outlined below.

- An open-loop allocation procedure applies to open-loop product systems where the material is recycled into other product systems and the material undergoes a change to its inherent properties.

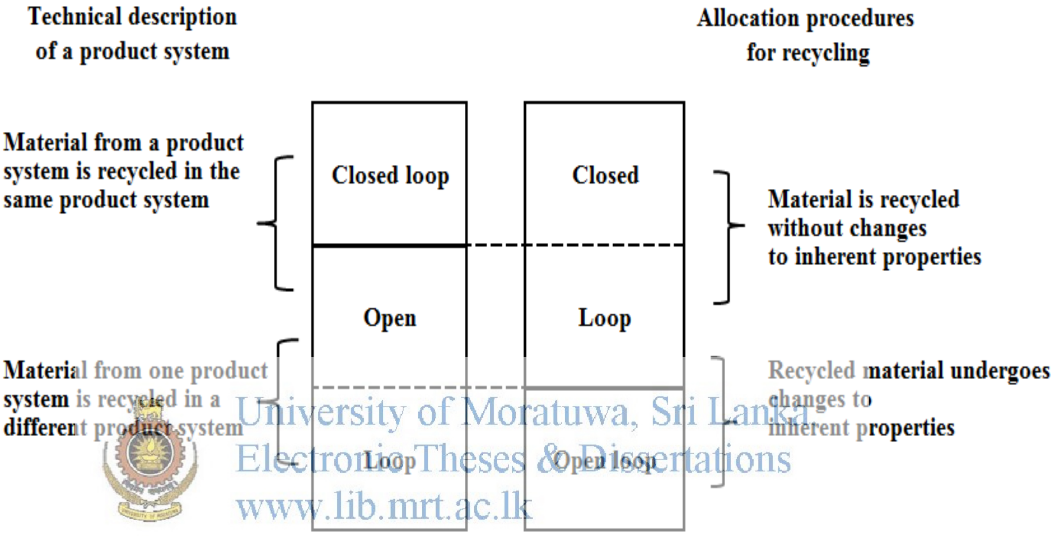


Figure 2.3: Distinction between a technical description of a product system and allocation procedures for recycling
Source: ISO 14044 (2006b)

The drawback in ISO 14044's (2006b) proposed procedure is that it does not consider allocation when the material is recycled more than once. Nyland et al. (2003), as cited in National Council for Air and Stream Improvement (NCASI, 2011), stated that if and when a mass fraction, "X", of a given material with initial mass, "M", is recycled "n" times, the amount of virgin material avoided, "R", is;

$R=MX_1+MX_1X_2+MX_1X_2X_3+\ldots+M\,X_1X_2X_{3\ldots}X_n$

If the fraction recycled is the same in each loop, then,

$\mathbf{R=M \sum X^n}$ ------------------------------------ **Equation (2.1)**

2.10 Impact Categories

Environmental impact categories, such as climate change, acidification, eutrophication, human toxicity, eco-toxicity, photochemical ozone formation, stratospheric ozone depletion, water resource depletion, mineral resource depletion, fossil fuel depletion, land use/biodiversity, and soil conservation are analysed in LCAs (Bengtsson & Howard, 2010; European Commission-Joint Research Centre-Institute for Environment and Sustainability [EC-JRC], 2011; ISO 14044, 2006b; Pennington et al., 2004; Shen et al., 2010).

The British Standards Institution (BSI, 2013), in its publication based on ISO/TS 14067:2013, provided detailed information on the requirements and guidelines for quantification and communication of product carbon footprints due to greenhouse gases.

2.10.1 Climate change (kg CO_2-eq.)

Heat is trapped in the Earth's atmosphere by the adsorption of infrared of reflected sunlight, causing changes in the earth's climate. Carbon dioxide, methane, nitrous oxide and halocarbons are the main anthropogenic emissions (Intergovernmental Panel on Climate Change [IPCC], 2007; Pennington et al., 2004). The emissions are converted to carbon dioxide equivalents (kg CO_2-eq.) for analysis.

The Global Warming Potential (GWPs), developed by the Intergovernmental Panel on Climate Change (IPCC), evaluated the relative contribution of different chemical emissions (CO_2, N_2O and CH_4) to climate change. The values were expressed in one mass unit of carbon dioxide according to different time scales (20,100 and 500years.)

Various modelling and forecasting techniques are used to predict climate changes, but no system can be singled out as being universally acceptable for building a scientifically-robust link between radiative forcing, temperature and ecosystem impacts (EC-JRC, 2011).

2.10.2 Photo-oxidant formation potential (kg C_2H_4-eq.)

The formation of ozone in the troposphere by the oxidation of nitrogen oxides, volatile organic compounds and carbon monoxide under the sunlight is expressed in terms of ethylene equivalence (kg C_2H_4-eq.). The spatial differentiation was found to be more important than was differentiation between the substances for vegetation impacts, and in particular, for human health impacts, in certain regions. EC-JRC (2011) recommended EDIP 2003, which respected the non-linearity of photochemical ozone formation, and addressed both human health and vegetation impacts. (It provided spatially differentiated characterisation factors, as well as overall site-generic factors for Europe, but adaptation to other continents is not straightforward.)

EC-JRC (2011) discussed the evaluation criteria of models, such as EcoSense, EPS200, LIME and ReCiPe. Grant and Peters (2009), as cited in Bengtsson and Howard (2010), suggested omitting the photo-oxidant formation category from routine LCAs, unless urban transport impacts are included in the study.

2.10.3 Stratospheric ozone layer depletion (kg CFC11-eq.)

The loss of UV absorption capacity due to ozone destruction in the stratosphere has led to a higher level of UVB reaching Earth’s surface, which, in turn, has been implicated in an increase of certain health risks (e.g., skin cancer). Ozone depletion potentials (ODPs), published by the World Meteorological Organisation (WMO), express the ozone depleting capacity of chlorofluorocarbons (CFCs), hydro-chlorofluorocarbons (HCFCs) and halons relative to the reference substance CFC-11 (World Meteorological Organisation, 1991, as cited in Pennington et al., 2004). The stratospheric ozone layer depletion is expressed in terms of chlorinated fluorocarbon 11 equivalence (kg CFC11-eq.).

ReCiPe considers the increase in ultraviolet (shortwave) levels, population density, original skin colour and other factors in its model. In practice, common ODP substances have a lifetime that is shorter than 100 years, allowing for the adaptation of the 100-year time frame (EC-JRC, 2011).

2.10.4 Acidification (kg SO_2-eq.)

The increase of hydrogen ion concentration in water and soil systems due to acidifying pollutants is calculated as the sulphur dioxide equivalence in the characterisation modelling. The ideal model should consider environmental relevance, such as atmospheric fate and soil sensitivity for acidifying emissions.

EC-JRC (2011) recommended AE (Accumulated Exceedance), which includes atmospheric and soil fate factors sensitive to emissions scenarios. EC-JRC (2011) also distinguished between loads to non-sensitive and sensitive areas. EC-JRC (2011) suggested the model developed by Van Zelm and colleagues in 2007 (as described in ReCiPe methodology) as an interim model, due to lack of scientifically robust methods for acidification.

2.10.5 Eutrophication (kg PO_4-eq.)

Eutrophication is associated with environmental impacts in both terrestrial and aquatic systems due to excessively high levels of nutrients that lead to shifts in species composition and increased biological productivity (Bengtsson & Howard, 2010). It is expressed in phosphate equivalence.

EC-JRC (2011) recommended models such as AE (Accumulated Exceedance), and CML2002 and EDIP2003 for terrestrial eutrophication, as well as ReCiPe, CML, TRACI and EDIP2003 for aquatic eutrophication.

2.10.6 Resource depletion

The consumption of resources faster than the rate of replenishment leads to resource depletion. This is expressed in the quantity of material used. The impact evaluation methods are based on the amount of the deposits, extraction rates or energy consumption (Pennington et al., 2004).

Energy demand (MJ)

The embodied energy is expressed in MJ; and is used as a proxy measure for other classes of impacts. The scope may be limited to only non-renewable fuel resources consumed (Bengtsson & Howard, 2010).

Water use (kg)

The water use needs to be related to the local scarcity of water. This enables differentiation between situations where water extraction has different impact levels. That is the assessment of water depletion in terms of the consequential impacts on the ecological function of bodies of water. Due to the cyclical and integrated nature of the water cycle, impacts on any aspect of the water cycle – extraction of surface flow, extraction of groundwater, alteration of water quality (chemical and physical characteristics), alteration to stream conditions (e.g., riparian vegetation) and alteration of climatic conditions – have flow-on impacts on the other components (Bengtsson & Howard, 2010).

Abiotic resource depletion (non-renewable fuels and minerals)

“Abiotic resources” are natural resources (including energy resources), such as iron ore, crude oil and wind energy, which are regarded as non-living (VROM, 2002). Abiotic resource depletion is expressed in kg of antimony equivalents or quantity of material used. EC-JRC (2011) discussed the principles of midpoint methods like Exergy, Swiss Ecoscarcity 2007 (energy), CML 2002, EDIP 1997, MEEUP and Swiss Ecoscarcity (water), in terms of their availability for “abiotic resource depletion.” In addition, the report compared endpoints or damage effects that indicated methods such as Eco-indicator 99, EPS2000 and IMPACT 2002+. In the general context of characterisation, the midpoint methods provide indicators (e.g., greenhouse gas emission) for the comparison of environmental effects at a level of a cause-effect chain between emissions/resource consumption and the endpoint level, whereas the endpoint methods provide indicators (e.g., global average temperature increase) at or closer to the level of areas of protection (i.e., human health, ecosystem and natural resource).

2.11 Data

2.11.1 Types and sources of data

Data selected for an LCA depend on the goal and scope of the study. Such data may be collected from the production sites associated with the unit processes within the system boundaries, or they may be obtained or calculated from other sources (ISO 14044, 2006b). The data are generally available at the building block level in most databases, i.e., for combinations of processes such as “electricity production” or “aluminium production.” They are frequently obsolete, incomparable, or of unknown quality (VROM, 2002; VROM & CML, 2001). In practice, all data may include a mixture of measured, calculated or estimated data.

As part of the emissions-to-air process, emissions of carbon monoxide, carbon dioxide, sulphur oxides and nitrogen oxides, as well as other types of emissions, may be separately identified. Emissions to air and discharges to water and soil often represent releases from point or diffuse sources, after passing through pollution control devices. These data also include fugitive emissions, when significant. Indicator parameters may include, but are not limited to, biochemical oxygen demand (BOD), chemical oxygen demand (COD), absorbable organic halogen compounds (AOX), total halogen content (TOX) and volatile organic chemicals (VOC). In addition, data representing noise and vibration, land use, radiation, odour and waste heat are also collected (ISO 14044, 2006b).

2.11.2 Data analysis

When modelling a system, the data that are most relevant and best represent the system depend on the purpose of the study. The practitioner has to decide whether to use site-specific data or data representing the average of a population of similar processes. In addition, the practitioner must decide whether to use data representing the average behaviour of a process (or population of processes) or data representing marginal performances. The issue of average versus marginal was discussed in the SETAC working group on the enhancement of inventory methodology, and was discussed again in the LCANET report (Grisel et al., 1997; Tillman, 2000).

Grisel et al. (1997), in their LCANET report, in addition to Tillman (2000), recommend data representing averages over a population of processes for retrospective (accounting) LCAs (e.g., when the LCA is meant to support decisions on regulatory measures) and data representing different types of marginal performances where effects of changes are modelled (except for long-term strategic planning, where expected future averages are recommended). Yu and Tao (2009) proposed the Monte Carlo simulation as a tool for handling the uncertainty that comes from different sources.

2.11.3 Treatment of missing data

Data gaps are inherent in many methodological problems, and often lead to high level of uncertainty. Any data found to be inadequate during the validation process should be replaced. Similarly, missing data should be identified, treated and documented (ISO 14044, 2006b; VROM, 2002).

2.12 LCI

In general, the greatest difficulty that LCA practitioners face is the time consuming nature of gathering data. Open source data, such as BEES and other available databases, provide some assistance. However, the inconsistency and inapplicability of available data are common problems, while obtained data that is discrete, static and linear, containing many assumptions, is indeed a great challenge.

2.12.1 Simplification of LCI

Depending on the specific application and decision to be supported, the required level of detail, the acceptable level of uncertainty, and the available resources (time, human resources, know-how and budget), different strategies for simplification of the inventory analysis can be applied. Rebitzer et al. (2004) indicated three principles that could be applied.

1. Direct simplification of process-oriented modelling (refer to 2.12.2)
2. LCA based on economic input-output analysis (refer to 2.4.7)

3. Hybrid methods, which combine elements of process LCA with economic input-output approaches (refer to 2.4.9)

2.12.2 Simplification of process LCA

Hunt et al. (1998), as cited in Rebitzer et al. (2004), indicated that the success rate of simplification by different horizontal cuts, expressed as delivering the same ranking as detailed LCAs, was found to be rather arbitrary and dependent on the single application and reference flows. De Beaufort-Langeveld et al. (1997), as cited in Rebitzer et al. (2004), described three steps, namely screening (qualitative approaches, semi-quantitative methods, and quantitative approaches), simplifying (relevance, validity, compatibility with computational procedures, reproducibility, transparency) and reliability checking (uncertainty analysis, sensitivity analysis). These three steps were used in the simplifying process, based on the SETAC Europe Working Group’s findings on the subject of simplifying. USEPA (1997), as cited in Todd and Marry (1999), described nine approaches that could be used to streamline LCA (see Table 2.2).

Table 2.2: Streamlining LCI approaches

Streamlining approach	**Application procedure**
Removing upstream components	Disregard processes prior to final product manufacture and consider fabrication into finished product, consumer use and disposal.
	Application: Focus on the reduction of downstream environmental impacts by building in recyclability or reusability.
	Advantage: This eliminates the issue of exclusive vendor data, one of the more difficult issues in LCA.
	Disadvantage: Important environmental consequences of raw material extraction or production might be eliminated from consideration, leading to sub-optimisation.
Partially removing upstream components	Disregard processes prior to final product manufacture, except for the step just preceding the final product manufacture. Might include raw material extraction and pre-combustion processes for fuels used to extract raw materials.
	Application/Advantages/Disadvantages: Similar to above.
Removing downstream components	Disregard all processes after final material manufacture.
	Application: To identify environmentally sound materials or processes.
	Advantage: Encourage vendors and suppliers to provide materials that have improved environmental profiles.
	Disadvantage: The benefits of looking at the life cycle of the product are lost.
Removing up- and downstream components	Consider only product manufacturing phase.
	Application: Gate-to-gate analysis.
	Advantage: Ease of obtaining the required data.
	Disadvantage: Similar to above.

Using specific entries to represent impacts	Select entries to approximate results in each impact category based on mass and subjective decisions.
	Application: Focus on high priority issues.
	Advantage: It focuses on the issues of importance to the user. Particularly useful when regional considerations are of critical importance.
	Disadvantage: Decisions made as a result of the study might not be the best for the areas of protection.
Using specific entries to represent LCI	Select entries from the individual processes that correlate with full LCI results, and disregard other entries.
	Application/Advantages/Disadvantages: Similar to above.
Using " show-stoppers" or "knockout criteria"	Criteria are established that, if encountered during the study, could result in an immediate decision.
	Application: When examining identified criteria.
	Advantage: It focuses on the issues of importance to the user.
	Disadvantage: May not yield the best result for the areas of protection.
Using qualitative as well as quantitative data	Use dominant values within each phase and exclude other values.
	Application: When considering environmental factors such as biodiversity and habitat issues which are not easily quantifiable.
	Advantage: All potential environmental issues are detected at each phase.
	Disadvantage: Difficulty in assessing the importance of each environmental concern in the overall life cycle, as well as product comparison.
Using surrogate process data	Replace selected processes with similar systems where the data are readily available.
	Application: When the relevant data are not available.
	Advantage: Estimates can be developed for data that would otherwise be unavailable.
	Disadvantage: The surrogates must be chosen very carefully to ensure that the surrogate truly represents the product, material, or process under the study.
Limiting the constituents studied to those meeting a threshold volume	Consider elements that reach a certain percentage by mass or some other factor.
	Application: Focus on hot-spots.
	Advantage: Limit the number of items that are likely to be the most important.
	Disadvantage: May focus only on volume and disregard hazard or toxicity by overlooking important environmental effects.

2.13 Life Cycle Impact Assessment (LCIA)

The impact assessment phase of LCA is aimed at evaluating the significance of the potential environmental impacts using the LCI results. The process involves associating inventory data with specific environmental impact categories and category indicators, thereby attempting to understand potential impacts. Issues such as choice, modelling and evaluation of impact categories could introduce subjectivity into the LCIA phase. Therefore, transparency is critical to the impact assessment to ensure that assumptions are clearly described and reported (ISO 14040, 2006a; VROM, 2002). Table 2.3 displays general terms used in LCIA with examples as stated in the ISO standards.

Table 2.3: General terms used in LCIA

Term	**Example**
Impact category	Climate change
LCI results	Amount of a greenhouse gas per functional unit
Characterisation model	Baseline model of 100 years of the intergovernmental panel on climate change
Category indicator	Infrared radiative forcing (W/m^2)
Characterisation factor	Global warming potential (GWP_{100}) for each greenhouse gas (kg CO_2 – equivalents/kg gas)
Category indictor result	Kilogram of CO_2 – equivalents per functional unit
Category endpoints	Coral reefs, forests, crops
Environmental relevance	Infrared radiative forcing is a proxy for potential effects on the climate, depending on the integrated atmospheric heat adsorption caused by emissions and the distribution over time of the heat absorption

Source: ISO 14044 (2006b)

Figure 2.4 illustrates the general steps of an LCIA, as stated in ISO 14040 (2006a). The fundamental principles and relationships that are relevant for the terms, which are shown in Table 2.3, are explicitly discussed in Chapters 2.15, 2.16 and 2.17.

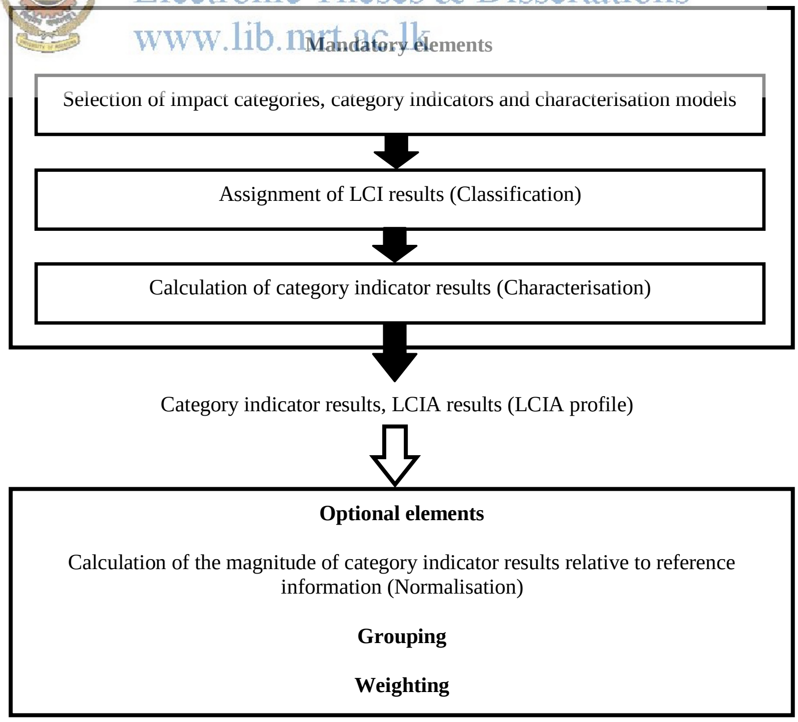


Figure 2.4: Elements of LCIA phase
Source: ISO 14044 (2006b)

ISO 14040 (2006a) did not recommend that LCIA be the sole basis of any comparative assertion that will be disclosed to the public regarding the overall environmental superiority or equivalence. This is because additional information is required to overcome certain inherent limitations, including value-choices, exclusion of spatial, temporal, threshold and dose-response information, relative approach and the variation in precision among the impact categories. Furthermore, ISO 14040 stated that LCIA results do not predict impacts on category endpoints, exceeding thresholds, safety margins or risks.

2.14 Classification

Under classification, the environmental interventions qualified and quantified in the inventory analysis are assigned, on a purely qualitative basis, to the various pre-selected impact categories (Ministry of Housing, Spatial Planning and the Environment [VROM-DGM], 2002). The assignment of interventions requires scientific analysis of relevant environmental processes (Hoffman et al., 1997). The interventions that contribute to more than one impact category demand that the assignment of the inventory values be based on either the parallel mechanism (e.g., SO_2 is apportioned between the impact categories of human health and acidification) or the serial mechanism (e.g., NO_x can be classified to contribute to both ground-level ozone formation and acidification) (ISO 14044, 2006b).

2.15 Characterisation

Characterisation models reflect the environmental mechanism by describing the relationship between the LCI results, category indicators and, in some cases, category endpoint(s). The characterisation model is used to determine the characterisation factors. The environmental mechanism is the total of the environmental processes related to the characterisation of the impacts. Figure 2.5 illustrates a characterisation mechanism of acidification (concept of category indicators) (ISO 14044, 2006b).

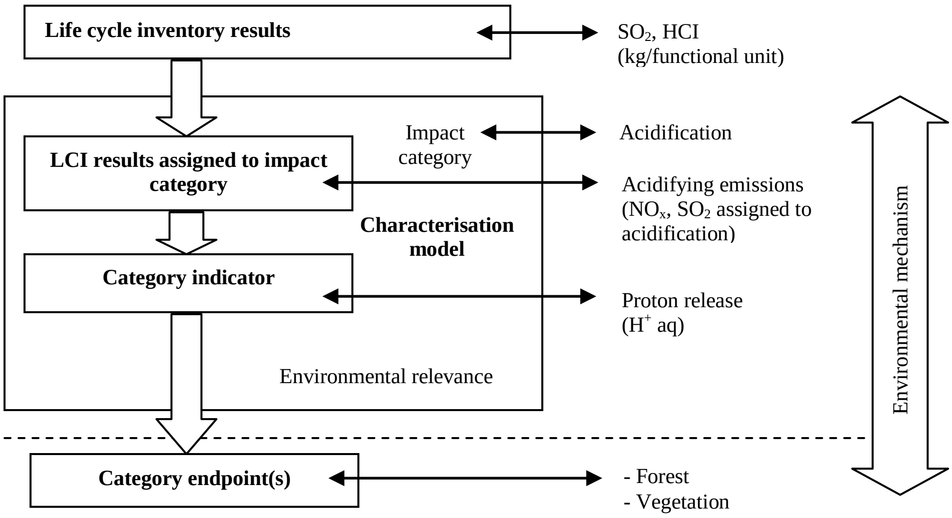


Figure 2.5: Characterisation mechanism of acidification
Source: ISO 14044 (2006b)

Depending on the environmental mechanism, goal, and scope, spatial (space-relevant) and temporal (time-relevant) differentiation of the characterisation model that relates the LCI results to the category indicator is considered (refer to **Appendix A**). The fate and transport of the substances are simply part of the characterisation model (ISO 14044, 2006b). The Danish Ministry of the Environment (2005), in their study, showed the advanced techniques of spatial differentiation in LCAs.

2.16 Category Indicator

ISO 14044 (2006b) stated that the category indicators that were intended to be used in comparative assertions that needed to be disclosed to the public, as a minimum, needed to be scientifically and technically valid, i.e., using a distinct identifiable environmental mechanism and/or reproducible empirical observation, as well as being environmentally relevant, i.e., have sufficiently clear links to the category endpoint(s) including, but not limited to, spatial and temporal characteristics.

2.17 Selection of Impact Categories, Category Indicators and Characterisation Models

ISO 14044 (2006b) made the following recommendations for the selection of impact categories, category indicators and characterisation models:

- The impact categories, category indicators and characterisation models should be internationally accepted, i.e., based on an international agreement or approved by a competent international body.

- The impact categories should represent the aggregated impacts of inputs and outputs of the product system on the category endpoint(s) through the category indicators.

- Value-choices and assumptions made during the selection of impact categories, category indicators and characterisation models should be minimised.

- The impact categories, category indicators and characterisation models should avoid double counting unless required by the goal and scope definition, for example, when the study includes both human health and carcinogenicity.

- The characterisation model for each category indicator should be scientifically and technically valid, and based upon a distinct identifiable environmental mechanism and reproducible empirical observation.

- The extent to which the characterisation model and the characterisation factors are scientifically and technically valid should be identified.

- The category indicators should be environmentally relevant.

2.18 Normalisation

Normalisation consists of calculating the magnitude of the category indicator results relative to reference information in order to better understand the relative magnitude for each indicator result of the product system under study (ISO 14044, 2006b; NCASI, 2011; VROM 2002).

2.19 Weighting (Valuation)

Weighting is an optional step of LCIA where the indicator results for each impact category are assigned numerical factors according to their relative importance, and then multiplied by these factors before possibly being aggregated (VROM, 2002). The numerical factors are based on value choices in order to facilitate a comparison across impact category indicators or normalised results. In general, scientific aspects in natural science, social and behavioural science, as well as in economics influence the weighting methods (ISO 14044, 2006b; NCASI, 2011; Pennington et al., 2004).

2.20 Improvement Analysis: Life Cycle Interpretation

Under “Life Cycle Interpretation” or “Improvement Analysis”, the results of the analysis (LCA study), as well as all choices and assumptions made, are evaluated in terms of soundness and robustness, and finally, conclusions are drawn. The main elements of the interpretation phase include an evaluation of the results (in terms of consistency and completeness), an analysis of the results (in terms of robustness), and the formulation of the conclusions and recommendations of the study (VROM, 2002). ISO 14040 (2006a) stated:

> *Life cycle interpretation provides a readily understandable, complete and consistent presentation of the results of an LCA, in accordance with the goal and scope definition of the study and which reaches conclusions, explain limitations and provide recommendations.*
>
> *The results indicate potential environmental effects; and that they do not predict actual impacts on category endpoints, the exceeding of thresholds or safety margins or risks.*
>
> *The interpretation phase, in certain cases, involve the iterative process of reviewing and revising the scope of the LCA, as well as the nature and quality of the data collected in a way which is consistent with the defined goal.(p.16)*

With each iteration, the level of uncertainty is expected to reduce. The assessment is completed when the results are sufficiently certain to adequately answer the questions that were posed in the goal and scope (Hauschild et al., 2005).

Preferably, decisions within an LCA should be based on natural science. If this is not possible, other scientific approaches, such as social or economic sciences, could be used or international conventions might be referred to. If neither a scientific basis exists nor a justification based on other scientific approaches or international conventions is possible, then, as appropriate, decisions may be based on value choices (ISO 14040, 2006a).

2.21 Transparency

Due to the inherent complexity in LCA, transparency is an important guiding principle in executing LCAs, in order to ensure the proper interpretation of the results (ISO 14040, 1997). The ISO standards present several requirements and recommendations to ensure transparency. Transparency is important when comparing the results of different LCA studies, where the assumptions and context of each study need to be equivalent.

2.22 Evaluation

In order to use LCA as a tool for decision-making, information is needed on the robustness of the results. This element of the interpretation phase assesses the influence on the variation in the process data, model choices and other variables (VROM, 2002). Uncertainties can increase as the modelling is extended along the mechanism – a model of higher complexity, usually one that explicitly represents more of an environmental mechanism or one that allows for a higher spatial/temporal resolution, can involve more explicit assumptions and might have higher input data requirements (Pennington et al., 2004). ISO 14044 (2006b) stated that an analysis of the results for both uncertainty and sensitivity is important for studies that are used in comparative assertions for public disclosure.

2.22.1 Sensitivity analysis

The sensitivity analysis assesses the influence of the variations in process data, model choices and other variables on the results (VROM, 2002). This results in exclusion of life cycle stages or unit processes when a lack of significance is shown by the sensitivity analysis, exclusion of inputs and outputs that lack significance to the results of the study, or inclusion of new unit processes, inputs and outputs that are significant (ISO 14044, 2006b).

2.22.2 Uncertainty analysis

A systematic procedure to quantify the uncertainty is needed in the results of a life cycle inventory analysis due to the cumulative effects of model imprecision, input uncertainty and data variability (ISO 14040, 1997). This uses empirical data on the uncertainty ranges of specific data to calculate the total error range of the results (VROM, 2002). For this aspect, integrating fuzzy multi-criteria has also been proposed as an alternative to handling the uncertainty in data (Benetto, Dujet, & Rousseaux, 2008; Tan, Culaba, & Aviso, 2008; Wang, 2010).

2.23 Summary

LCA is predominantly quantitative in character. Where this is not possible, qualitative aspects are also taken into consideration. LCA models the life cycle of a product as its product system, which performs one or more defined functions. It can be considered as a typical static simulation model. The essential property of a product system is characterised by its function, and is not defined solely in terms of the final products.

In general, all variants of LCAs are conceptualised around one basic framework and methodology while the application depends on the specific occasion. In accounting (retrospective) LCAs, the systems include all life cycle stages from cradle-to-grave, whereas activities contributing to the environmental consequences of a change are investigated in a consequential (prospective) LCA. LCA models, such as “cradle-to-grave” and “cradle-to-cradle,” have the visibility of all life cycle stages of a product, and hence, they avoid sub-optimisation, while “gate-to-gate” (or cradle-to-gate) has a narrow perspective. Hybrid LCAs facilitate life cycle assessments with incomplete information, and enable the creation of models that significantly reduce the truncation error inherent in process-LCAs, while reaching to process specificity.

However, a generalised methodology that can be applied to the apparel industry is not readily available in the literature.

The functional unit quantifies the identified functions of the product. As a result, both LCI and LCIA profiles are related to the functional unit. The mathematical relationships that describe these mechanisms in principle are non-linear, dynamic and will often show hysteresis and irreversibility.

Depending on the specific application and decision to be supported, the required level of detail, the acceptable level of uncertainty, and the available resources, simplifications of the inventory analysis can be accomplished through direct simplification of process-oriented modelling, LCA based on an economic input-output analysis or the hybrid method.

All data may include a mixture of measured, calculated or estimated data, and may be collected on-site or from other sources. Furthermore, a decision has to be made about whether to use site-specific data or data representing an average over a population of similar processes and whether to use data representing average behaviour of a process (or population of processes) or data representing marginal performance. When the allocation procedure is applied, the amount of virgin material that is avoided due to re-use and recycling of products should also be considered.

The midpoint characterisation methods provide indicators for the comparison of environmental effects at the level of a cause-effect chain between emissions/resource consumption and the endpoint level, whereas the endpoint methods provide indicators at or closer to the level of the areas of protection. However, the credible science-based damage effect indicating methods need to be further explored. Issues, such as choice, modelling and evaluation of impact categories, can introduce subjectivity into the LCIA phase. Generally, the scientific aspects of the natural science, social and behavioural science, and economics, influence the weighting methods. Furthermore, the category indicators need to be scientifically and technically valid. In the current context, LCA does not provide the framework to identify impacts in a localised condition.

Chapter 3

FIBRE-TO-FASHION LCA

3.1 Introduction

The vibrant textile and apparel sector, with its heterogeneous manufacturing and consumption patterns, often strain the environment, requiring tools for the comparison of present technologies, as well as for the application of cleaner technologies. In the current context, environmental sustainability is turning out to be the norm within both the international and the Sri Lankan apparel communities. However, regardless of its widespread acceptance as a guiding principle, a comprehensive framework (where the analysis of environmental sustainability is feasible) is not commonly available for those who are interested, especially in the Sri Lankan society.

LCA tools, such as Eco-Indicator 95 and 99, Environmental Priority System, Eco-Points Method, USES 4.0, IMPACT 2002+ and GaBi are categorised into dedicated software packages that are intended for practitioners and tools with the LCA in the background that are intended for people who want LCA-based results without having to actually develop the LCA data and impact measures. Winkler and Bilitewski (2007) and Cotetiu, Vasile and Banica (2006) provided comprehensive information of the available tools. However, an LCA tool that could be used to analyse the life cycle of a garment produced in Sri Lanka could not be found.

“Fabric”, the main raw material of a garment, involves a series of processing, starting with fibre manufacturing. Afterwards, fibres are spun into yarn during yarn manufacturing, and finally, yarns are woven or knitted to produce the pre-defined fabric structures during fabric manufacturing. The fabrics are normally subjected to dyeing and finishing before being used in garment making. The energy requirements, material inputs, wastages and emissions can only be calculated through a detailed analysis of each processing step involved. With reference to the literature review, an LCA methodology to suit the apparel industry was sought. The steps that needed to be followed to execute the LCA (end product: garment) are listed in chronological order. The model is coined as “**Fibre-to-Fashion LCA**” for easy reference.

3.2 Fibre-to-Fashion LCA Methodology

3.2.1 Elements of the Methodology

First, set the goal of the study by stating the intended application, motive for carrying out the study and the expected audience (ISO 14040, 2006a). Then, define the scope by declaring technical information such as the functional unit, system boundaries, impact categories, assumptions/limitations (ISO 14040, 2006a; VROM, 2002).

Model the life cycle of a product as its product system (Rebitzer et al., 2004). The system may consist of a set of unit processes that are linked to one another by flows of intermediate products and/or to other product systems by product flows, and to the environment by elementary flows. The elementary flows include the use of resources and releases to air, water and land associated with the system (ISO 14040, 2006a).

Define the system boundary to include the unit processes, where the choice of elements of the physical system to be modelled depends on the goal and scope definition of the study, its intended application and audience, the assumptions made, data and cost constraints, and cut-off criteria. The system boundary may include several life cycle stages, unit processes and flows. The contribution of mass, energy and environmental significance can be investigated as cut-off criteria for inputs (ISO 14044, 2006b).

Decide the type of impact categories to be investigated in the study. These may include climate change (kg CO_2-eq.), photo-oxidant formation potential (kg C_2H_4-eq.), stratospheric ozone layer depletion (kg CFC11-eq.), acidification (kg SO_2-eq.), eutrophication (kg PO_4-eq.) and resource depletion (Bengtsson & Howard, 2010; European Commission-Joint Research Centre-Institute for Environment and Sustainability [EC-JRC], 2011; ISO 14044, 2006b; Pennington et al., 2004; Shen et al., 2010).

Depending on the specific application and decision to be supported, the required level of detail, the acceptable level of uncertainty, and the available resources (time, human resources, know-how and budget), different strategies for simplification of the inventory analysis can be applied. The main principles are: direct simplification of process-oriented modelling; LCA based on economic input-output analysis; hybrid method (Rebitzer et al., 2004). The simplification of the process-oriented LCA can be done by: removing upstream components or partially removing upstream components; removing downstream components; removing up- and downstream components; using specific entries to represent impacts; using specific entries to represent LCI; using "showstoppers" or "knockout criteria"; using qualitative as well as quantitative data; using surrogate process data; and limiting the constituents studied to those meeting a threshold volume (USEPA, 1997, as cited in Todd and Marry, 1999).

The practitioner has to decide whether to use site-specific data or data representing the average of a population of similar processes. In addition, the practitioner must decide whether to use data representing the average behaviour of a process (or population of processes) or data representing marginal performances (Grisel et al., 1997; Tillman, 2000). All data may include a mixture of measured, calculated or estimated data, and may be collected from the production sites associated with the unit processes within the system boundary, or they may be obtained or calculated from other sources (ISO 14044, 2006b). Mention data gaps in the system, as well as assumptions made.

Allocate the input or output flows of the process or product system between the product system under study and other product systems. Apply allocation procedures uniformly and approximate fundamental input/output relationships and characteristics (ISO 14044, 2006b). A closed-loop allocation procedure needs to be applied to closed-loop product systems and open-loop product systems where no changes occur in the inherent properties of the recycled material. Similarly, apply an open-loop allocation procedure to open-loop product systems where the material is recycled into other product systems and the material undergoes a change to its inherent properties (ISO 14044, 2006b).

Following the data collection and allocation, calculation procedures may include: relating data to unit processes; relating data to the reference flow of the functional unit. Thus, LCI needs to be built up (ISO 14040, 2006a). Then, associate inventory data with specific environmental impact categories and category indicators (ISO 14040, 2006a; VROM, 2002). First, assign the inventory input and output data to potential environmental impacts based on scientific analysis of relevant environmental processes (ISO 14044, 2006b). Second, choose a characterisation model that reflects the environmental mechanism (complete environmental processes) by describing the relationship between the LCI results and category indicators. Derive the characterisation factors using the characterisation model (ISO 14044, 2006b).

Calculate the magnitude of category indicator results relative to reference information (optional). Then, convert indicator results of different impact categories by using numerical factors based on value-choices (optional). Finally, generate conclusions and recommendations based on LCI and/or LCIA (ISO 14040, 2006a; NCASI, 2011; Pennington et al., 2004; VROM, 2002).

3.2.2 Schematic Representation of Fibre-to-Fashion LCA

The methodology described in Chapter 3.2.1 is illustrated in Figure 3.1.

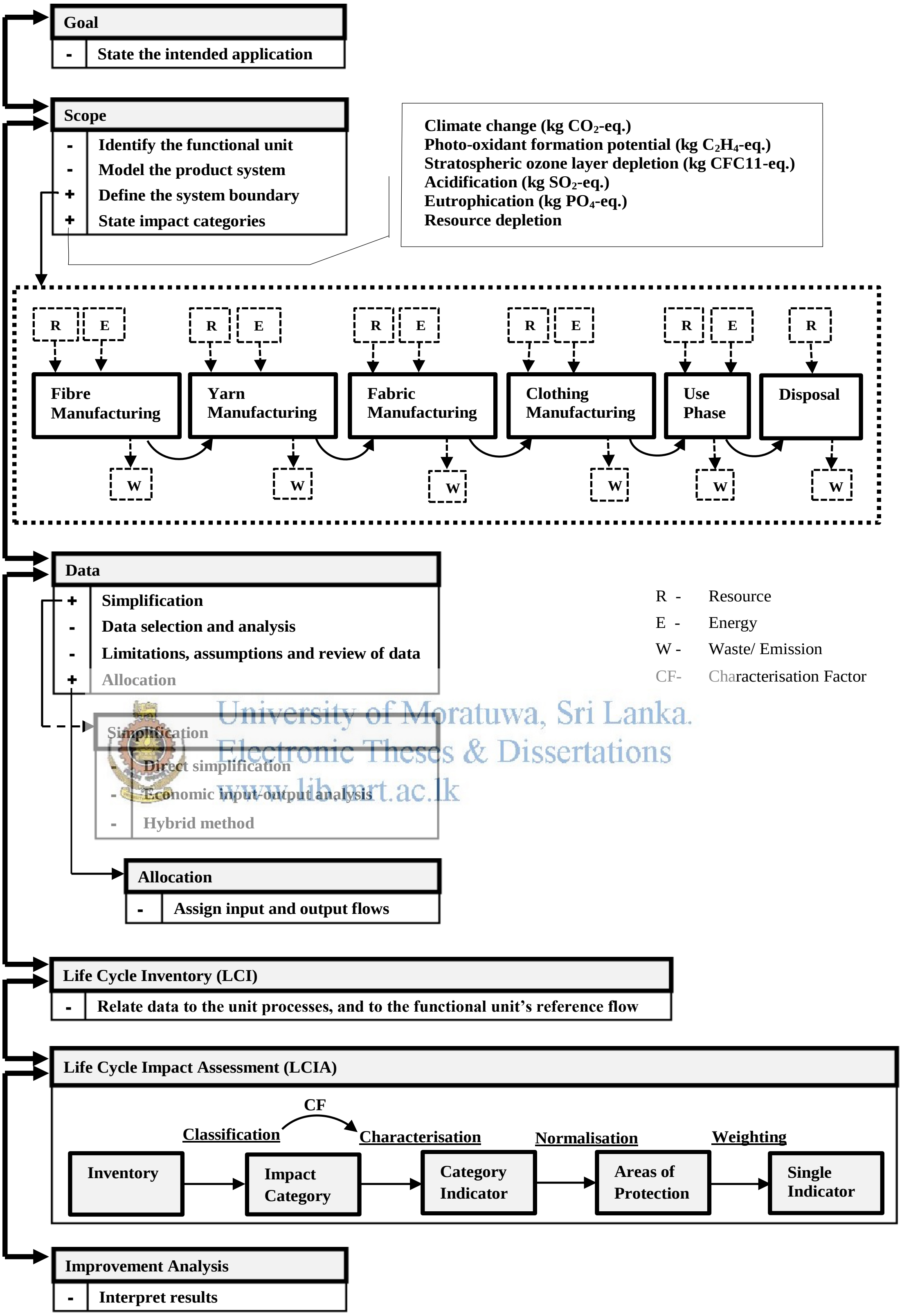


Figure 3.1: Fibre-to-Fashion LCA methodology

3.3 Application of Fibre-to-Fashion LCA

The life cycle of a garment can be distinguished by several phases such as fibre production, yarn production, fabric production, garment production and consumer use (including disposal), involving wide range of processes. The goal of an LCA study needs to be preciously identified in the beginning. This enables the optimum usage of available resources (e.g., time) to meet the purpose of the study.

The functional unit provides a reference of where the life cycle inventory data are related. The functional unit of an LCA study in the apparel industry is not necessarily defined as “one garment piece.” If applied, the interpretation of life cycle inventory data for fibre, yarn and fabric productions might be difficult. Therefore, the functional unit can be defined as 1,000kg of cotton woven fabric or similar.

As flows and processes in a garment’s life cycle are inter-linked to other product systems in a heterogeneous pattern, the system boundaries of an LCA need to be set. This leads to the exclusion and inclusion of processes, elementary flows and product flows. The simplification process could be considered prior to data gathering in order to keep the amount of data handling feasible within the scope.

When gathering data, deciding on whether to use site-specific data or data representing an average over a population of similar processes is required, along with determining whether to use data representing the average behaviour of a process (or population of processes) or data representing marginal performance. For example, regarding cotton-fibre production, fibres are grown in various regions, such the United States, India and Brazil. If an LCI is generated for each region, the results will vary due to factors, such as differences in irrigation patterns, type of chemical used, and transportation. Therefore, the LCA practitioner may wish to use the global average rather than site-specific data for cotton-fibre production. Then, with respect to the product system, the collected data are required to be related to the functional unit in order to build the LCI for the chosen product.

In the case of cotton production, two valuable co-products, namely cotton fibre and cottonseed, are produced. The cotton fibre is used mainly for the production of cotton fabrics, while cottonseed is used for various applications, such as viscose yarn/fabric production, as well as in the paper industry and food industry (e.g., cottonseed oil). Thus, if the system delivers more than one recognisable output, the environmental impacts need to be allocated. The allocation method (e.g., mass base, monetary value base) needs to be decided on the basis of the elements involved. When cotton cloths are moved for recycling, they might be resold or down-cycled. As a result, the environmental impact is reduced. Therefore, the amount of virgin material avoided needs to be taken in to the calculation. Thus, an allocation procedure for re-using and re-cycling needs to be adopted.

Carbon dioxide (CO_2) emissions due to electricity usage and transportation might stimulate global warming. (CO_2 emissions are partly offset for garments manufactured using fibre types such as cotton and ramie due to photosynthesis process during the plants' growth). Similarly, other emissions, wastes and consumption of resources contribute to different environmental impacts. Hence, the (major) impact categories that are relevant for a particular study need to be identified. When the emission of NO_x is considered, it might contribute to both ground-level ozone formation and acidification. Therefore, the assignment of inventory values to impact categories based on scientific rationale is required. That is the "classification" step. Then, the individual emissions, wastes, or consumption of resources that are already assigned to one particular impact category might need to be represented as a single indicator. This is achieved through the use of an emission/characterisation factor. For example, both CO_2 and nitrous oxide (N_2O) contribute to global warming, as expressed in "kg CO_2 equivalent". To express the result in one figure and unit, the amount of N_2O needs to be converted to a CO_2 equivalent. An emission/characterisation factor recognised by an international body can be used for the same purpose. Thus, *characterisation* of the individual inventory elements is required.

When a comparison between two products is required, the magnitude of the category indicator results relative to the reference information needs to be calculated (i.e., normalisation). Appropriate weightings based on value choice can be used to obtain the relative magnitude for each category indicator result. For example, if the environmental impacts of a 100% cotton garment and a 100% polyester garment are to be compared, the impact category results are required to be presented as a single value for ease of comparison. Finally, the results of LCI and LCIA analysis could be interpreted to reach conclusions, explain limitations and provide recommendations.

Chapter 4

CASE STUDY

4.1 Introduction

The LCA concept is quite new to Sri Lanka, and as thus, there was no record of LCA studies found for the apparel industry, which accounts for about half of the country’s total exports. Conversely, the global apparel and textile industry is moving towards achieving the goal of zero discharge of hazardous chemicals by 2020, with the focus on environmental sustainability having been steady since the 1990s. In order to achieve this challenging goal, mechanisms for disclosure and transparency regarding the hazardous chemicals used in the global supply chains have been identified as being important and necessary. Under such circumstances, it is necessary to conduct LCAs as a dissemination strategy of its vision.

4.1.1 Company history

The company in this study was incorporated as an apparel manufacturer in 1991. Since then, it has developed into an international fashion supplier, with an annual sales-turnover of US$75 million, producing more than 8 million high-quality garments at eight of its own factories located in Sri Lanka. In addition to its head office, design centre, and logistic division located in the heart of Colombo, the company provides customer support through its service office in Germany. At the present time, the company employs more than 7,000 workers to produce ladies outer wear for some global prestigious brands. The company’s vision is “To offer quality customer service through innovation, leadership and excellence, and to be responsive to changes in a competitive global environment.”

In addition, the company’s ethical and social standards go hand-in-hand with the Sri Lankan apparel community, which created its own ethos, “Garments without Guilt,” epitomising the synergy between ethical brands and apparel made in Sri Lanka. "Children have no business in our business" is just one of the principles governing this industry’s ethos.

4.1.2 Environmental policy

The company recognised the complexity in today's context, where emission, waste generation and consumption of resources, which occur at different phases in a product's life cycle, have led to toxicological stress on human health and ecosystems, stratospheric ozone-layer depletion, acidification, photo-oxidant formation and other environmental problems - the ever increasing need for working as a whole toward reconciliation and finding sustainable solutions. In 2013, the company stressed to all of its sourcing and manufacturing partners the importance of bringing the industry to a new level through the application of cleaner chemicals and technologies for a sustainable future. The company also presented its shared goal of achieving zero discharge of hazardous chemical (ZDHC) across the entire supply chain along with some of the global fashion brands by 2020. In addition, the results of this study could be used as a tool in its ZDHC campaign.

4.2 Goal

Goal	
-	State the intended application

The goal of the case study was to investigate the environmental performance of a 100% cotton garment using the fibre-to-fashion LCA model, and then to identify the methodical and practical limitations in executing a life cycle assessment in Sri Lanka with a target-audience of researchers and the apparel industry as a whole.

4.3 Scope

Scope	
-	Identify the functional unit
-	Model the product system
-	Define the system boundary
-	State impact categories

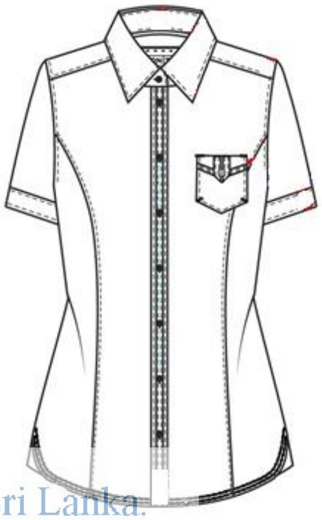
4.3.1 Functional unit

The 100% cotton blouse, with a mass of 0.146kg, was taken as the functional unit of the system. The description of the product is given in Figure 4.1. The chosen product (100% cotton blouse) was cut and sewn at one of the production factories belonging to an apparel manufacturing group in Sri Lanka. The type of components, manufacturing processes of components and the production process of the garment vary significantly from product to product. This heterogeneity makes it virtually impossible to identify a standard product for analysis. Thus, there are limitations to the adaptability of the available data and to the comparison of the results.

Product's description:
End product: Short-sleeve-blouse
Standard Allowed Minutes*: 29.82
Weight: 0.146kg

Fabrication:
Warp (yarn size in English count): 60Ne
Weft (yarn size in English count): 60Ne
Number of ends per inch: 104
Number of picks per inch: 88
Weight: 75gsm
Weave: 1/1, Plain
Fibre composition: 65/35 Indian cotton/USA cotton
Dyeing technique: Solid piece dyeing
Finished width: 58"
Other factors: Not considered

Functional unit:
100% cotton blouse with a mass of 0.146kg



*Standard Allowed Minutes: This represents the total number of minutes allowed to complete a process or operation in a standard environment for a standard worker.

Figure 4.1: Product's profile

The bill of materials is shown in Table 4.1. The components other than "fabric" are omitted from the analysis as "fabric" remains as the major component of the chosen product.

Table 4.1: Bill of materials

Component	Unit	Consumption
Fabric	m	1.32
Button	pcs	10
Thread [120ticket*]	m	320
Thread [220ticket]	m	140
Interlining	m	0.28
Care label	pcs	1
Size label	pcs	1
Main label	pcs	1
Packing materials	pcs	Not considered

*Ticket=Nmx3 Where Nm is the metric count of the thread.

4.3.2 Product system

Figure 4.2 shows a schematic diagram of the entire product system. All modelled flows are related to the functional unit, unless stated otherwise.

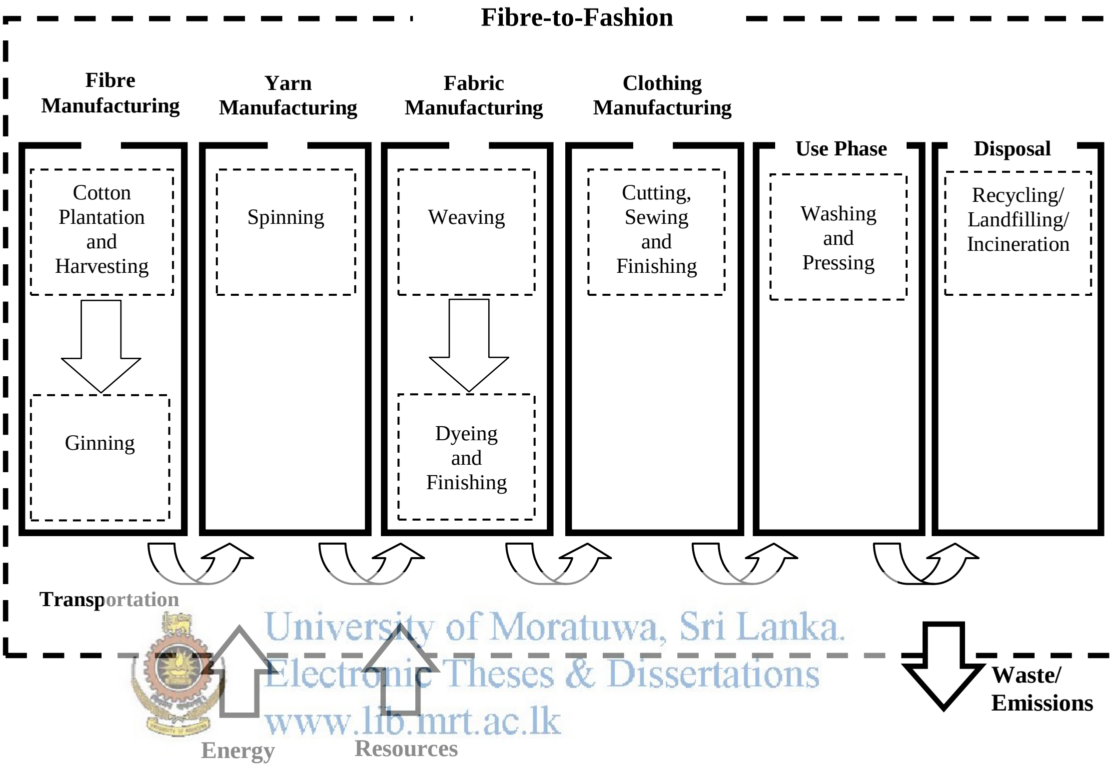


Figure 4.2: Schematic diagram of the product system

4.3.3 System boundaries

The main raw material (fabric) production and electricity generation were traced to the cradle. The emission to air was included whenever the data could be acquired and calculated with no duplications. The data were obtained from the literature, except for garment production, where site-specific data were used. Table 4.2 depicts the processes considered within the system boundaries.

Table 4.2: Spatial and temporal boundaries

Within the system boundaries	**Location**	**Time horizon**
Electricity generation	Sri Lanka	2011 ~ 2013
Raw material production (Fibre)	India and USA	2010 ~ 2012
Raw material production (Yarn)	India	2012
Raw material production (Fabric)	India	2012
Manufacturing of end products	Sri Lanka	2013
Transportation (Only port-to-factory [fabric] and factory-to-port [garments] are considered)	Sri Lanka	2013
Product use	USA	2013 ~ 2014
Outside system boundaries		
Land use	Sri Lanka/India/USA	2010 ~ 2013
Equipment and buildings	Sri Lanka/India/USA	2010 ~ 2013

4.3.4 Impact categories

The following impact categories were examined:

Climate change (kg CO_2-eq.)

Photo-oxidant formation potential (kg C_2H_4-eq.)

Stratospheric ozone layer depletion (kg CFC11-eq.)

Acidification (kg SO_2-eq.)

Eutrophication (kg PO_4-eq.)

Resource depletion

4.4 Data

Data	
-	Simplification
-	Data selection and analysis
-	Assumptions, limitations and review of data
-	Allocation

4.4.1 Simplification

In this study, certain principles of direct simplification of process-oriented modelling were considered. The information regarding this is mentioned in Chapter 4.4.3.

4.4.2 Data selection and analysis

In Table 4.3, the year and database relate to the data collection of the original data set; the column *technique representatives* indicates the extent to which the used data corresponded to the actual data set using the terminology as defined in GaBi (2007), as cited in Rinde (2008).

Table 4.3: Data profile

Dataset	**Year**	**Database**	**Technique Representativeness**
Fibre manufacturing	Not known	Literature	Partly representative
Fabric (including yarn) manufacturing	Not known	Literature	Partly representative
Electricity usage	2013	Finance department	Completely representative
LCI for electricity generation	2007, 2002	Literature	Partly representative
LCI for transportation	2005	Literature	Partly representative
Garment production	2013	Planning and Finance departments	Completely representative
Garment use (laundry)	Not known	Literature	Not representative

Completely representative: Same facility or documented standardised technique that reflects the facility where the data are collected.

Partly representative: Similar technologies are used, but there is no documentation stating this fact. Or, if no information exists regarding the actual processes used, it can be assumed that they are similar.

Not representative: It is documented that the processes used are not similar to/representative of the data collection. The main output product does, however, have a reasonable likeness with the main output from the original process.

No statement: Unknown processes and no qualified assumptions can be made.

4.4.3 Limitations, assumptions and review of data

- The fibres used in the product are grown in both the United States and India. The yarn production (through spinning of fibres) and fabric productions were done at one of the largest vertically integrated fabric mills in India. As site-specific data were not available for the study, the sector level data were considered for the fibre and fabric (including yarn) manufacturing processes.

- For the cotton fibre production, the collection of data from the three largest cotton producing countries (China, India and USA) and the calculation of a global average can be more appropriate due to the geographically variable nature of this segment. Similarly, the data for the fabric production phase can be taken from surveys among representative mills in the two largest cotton fabric producing countries (China and India) and presented/used as a global average.

- The procedure mentioned above was not feasible for this study due to limited resources. Therefore, this study used available data from the literature. Cotton Incorporated, the National Cotton Council and PE International carried out a joint project in 2011 to gather data relevant for cotton fibre and fabric production. However, the gathered data were not publicly available; their findings can be found in the report titled "Life Cycle Assessment of Cotton Fibre and Fabric."

- The overall CO_2 emission during the production phase of fibre due to burning of fossil fuel is partly offset because of photosynthesis in cotton plants. However, this was not considered for this study.

- The consumption of water during the cotton growth and harvesting depends greatly on the region where it grows. In certain part of the world, the irrigation is supported by the river water – direct rainfalls also result in reducing the demand for fresh water.

- The by-products of the cotton yield are used for viscose fibre production, as well as for animal feeding. However, these were not accounted for in this study due to insufficient industrial data. In addition, the data relevant for chemicals and raw materials (except cotton) were also ignored in this study.

- The effect caused by yarn quality, type of dyeing and finishing was not considered due to the unavailability of data.

- The data for the cut-and-sew was taken from the actual site, and the consumer use phase was supplemented by data available in the literature.

- The actual number of minutes taken by each product during garment production varied due to deviations in the efficiency of manual operations. However, such deviations were ignored in this study due to the unavailability of data.

- The life cycle data relevant for the production of one unit of electricity is different from country to country, depending on the composure of the power generation sources. Currently, the LCI relevant for the generation and distribution of one unit of electricity in Sri Lanka is not available due to insufficient data.

- Transportation distances were estimated using the tools available on the Internet. The transportations from country to country were ignored, as the frequent mode of shipment is sea freight where the emission per one functional unit was assumed to be insignificant.

- The number of washes and pressings during the use phase varies from product to product due to product’s care instructions, as well as the consumer behaviour. As actual data were not available, the data relevant for washing was obtained from the literature, and the pressing was ignored.

- The exact disposal method was not known for the chosen product. Hence, data relevant for product disposal were omitted from the calculation. In general, it gets decomposed and emits CO_2 and CH_4 when landfilled – the energy can be recovered when incinerated. In addition, the end product can even be recycled, and in this case, either open loop or closed loop allocation has to be made.

- As some data in this study were obtained from the literature, there is some degree of uncertainty in the results. However, the uncertainty was not quantified in this study.

4.4.4 Allocation

In this case study, the physical causality acted as the basis of allocation for each sub-process. Within the garment production unit, the allocation was made based on the standard allowed minutes of the chosen garment.

4.5 Life Cycle Inventory

Life Cycle Inventory (LCI)	
-	Relate data to the unit processes, and to the functional unit's reference flow.

In this section, LCI is formed and model processes are described in brief. An overview of the major flows in the system is presented in Figure 4.2.

4.5.1 Garment manufacturing

The end product was manufactured in Sri Lanka, whereas the main raw material, cotton fabric, was imported. The chosen product was manufactured together with different garment products (styles) in the same factory. Figure 4.3 represents the processes identified within the garment manufacturing process. A brief description of the sub-processes and elements related to those sub-processes is stated in Table 4.4.

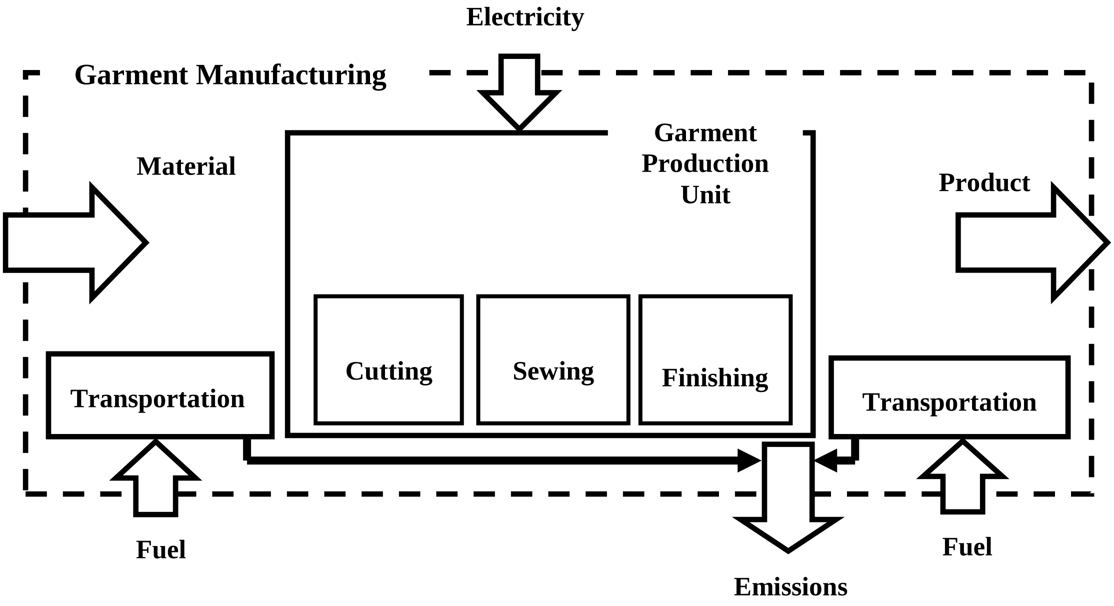


Figure 4.3: Schematic diagram of the garment manufacturing process

Table 4.4: Elementary flows of the garment manufacturing process

Process	Inflow	Outflow	Remarks
Transportation of fabric from port to factory	Fuel	Emissions	▪ The life cycle data of vehicles are ignored. ▪ The vehicle-maintenance is ignored.
Cutting	Electricity		▪ The life cycle data of buildings and machineries are ignored. ▪ The maintenance is ignored. ▪ The transportation of workers is ignored. ▪ The raw materials other than fabric (e.g., button, interlining) are ignored.
Sewing	Electricity		
Finishing	Electricity		
Transportation of garments from factory to port	Fuel	Emissions	▪ The life cycle data of vehicles are ignored. ▪ The vehicle maintenance is ignored.

4.5.2 LCI for electricity generation in Sri Lanka

Ceylon Electricity Board (2012) in their annual report entitled *Statistical Digest 2011*, stated that the total gross electricity generation for thermal, hydro and other was 59%, 40% and 1%, respectively, where the total gross electricity generation for 2011 was 11,528 GWh. In contrast, the total gross electricity generation for thermal, hydro and other was 70.8%, 22.9% and 6.3%, respectively, for 2012, where the total gross electricity generation was 11,895.8 GWh (Sri Lanka Sustainable Energy Authority, 2013). The category “other” represents sources such as wind and solar.

As the Ceylon Electricity Board’s statistical report for 2013 regarding the electricity generation for 2013 had not been released at the time of data analysis, the statistical data from 2012 was considered for calculation. Table 4.5 shows the calculation of LCI for electricity generation in Sri Lanka.

In this study, the LCI for one unit (KWh) of electricity in Sri Lanka was calculated as a sum of inflows and outflows of each power source in the national grid (see **Equation 4.1**). The data relevant for each source were obtained/estimated from the data available for other countries, as stated below.

$$\mathbf{LCI_e = \sum LCI_{(s)} * E_{(s)}} \qquad \text{-- } \textbf{Equation (4.1)}$$

Where,

LCI_e: LCI related to generation of 1 kWh in Sri Lanka

$LCI_{(s)}$: LCI of power supply source ***“s”***

$E_{(s)}$: Electricity generated by source ***“s”*** as a percentage of the total electricity generated

The life cycle inventory of **“thermal power generation and distribution”** in Sri Lanka was assumed to be the same as that of 1 kWh electricity generation for 2007 in China (Sha et al., 2012) (refer to **Appendix C**).

The **“thermal to hydroelectric power conversion”** was calculated on the basis of Bergerson and Lave’s (2002) report on coal and hydroelectric power related emissions (refer to **Appendix D**). The ratio of values was taken as the conversion factor (see **Equation 4.2**). The emissions to air from coal power generation were assumed to be same as that of thermal power.

$$CF_{(e)} = E_{(e,s)} / E_{(e,t)} \qquad \text{---} \textbf{ Equation (4.2)}$$

Where,

$CF_{(e)}$: Conversion factor of element ***“e”***

$E_{(e,s)}$: Value of element ***“e”*** related to power supply source ***“s”***

$E_{(e,t)}$: Value of element ***“e”*** related to thermal power generation

The **“thermal to wind power conversion”** was calculated on the basis of Bergerson and Lave’s (2002) report on coal and hydroelectric power related emissions (refer to **Appendix D**). The ratio of values was taken as the conversion factor (see **Equation 4.2**). The emissions to air from coal power generation were assumed to be the same as that of thermal power.

Table 4.5: LCI for electricity

Consumption/ Emissions		Units	Category (All values are given per kWh)					
			Thermal Power	Thermal to Hydro Conversion Factor (Estimated) – Equation (02)	Hydroelectric Power (Estimated)	Thermal to Wind Conversion Factor (Estimated) – Equation (02)	Wind Power (Estimated)	Generation of 1 kWh in Sri Lanka (Estimated) – Equation (01)
Fossil Fuel	**Raw coal**	**kg**	**0.48E+00**					**3.40E-01**
	Crude oil	**kg**	**3.31E-03**					**2.34E-03**
	Natural gas	**m^3**	**2.96E-03**					**2.10E-03**
	Coke oven gas	**m^3**	**2.92E-03**					**2.07E-03**
	Other gas	**m^3**	**4.81E-03**					**3.41E-03**
Pollutants	**CO_2**	**kg**	**0.97E+00**	5.93E-03	**5.75E-03**	9.53E-03	**9.24E-08**	**6.88E-01**
	CH_4	**kg**	**1.06E-05**	2.40E-03	**2.54E-08**	1.54E-03	**1.63E-08**	**7.51E-06**
	N_2O	**kg**	**1.51E-05**	3.86E-03	**5.83E-08**	2.95E-03	**4.45E-08**	**1.07E-05**
	SO_2	**kg**	**4.41E-05**					**3.12E-05**
	NO_2	**kg**	**5.44E-03**					**3.85E-03**
	CO	**kg**	**1.12E-03**					**7.93E-04**
	NMVOC	**kg**	**2.52E-04**					**1.78E-04**
	Dust	**kg**	**1.30E-03**					**9.20E-04**
	Industrial water	**kg**	**0.61E+00**					**4.32E-01**
	Coal fly ash	**kg**	**4.41E-02**					**3.12E-02**

4.5.3 Electricity consumption

The electricity usage, number of garments shipped and total number of standard allowed minutes of shipped garments are listed in Table 4.6. The number of electricity units per standard allowed minute is calculated as given below.

$$\mathbf{E_{sm} = E\ (t)/\ M\ (t)} \qquad \text{---} \ \textbf{Equation (4.3)}$$

Where,

E_{sm}: Number of electricity units per standard allowed minute

E (t): Total number of electricity units used for month ***"t"***

M (t): Total number of standard allowed minutes of garments shipped during month ***"t"***

Table 4.6: Statistics on electricity usage vs. shipped quantity

Month (in 2013)	**Electricity Unit (kWh)**	**Number of Garments Shipped (pieces)**	**Total Standard Allowed Minutes of Shipped Quantity**	**Electricity Units per Standard Allowed Minute (kWh)**
January	54,539	59,520	2,022,609	0.03
February	52,551	28,673	865,458	0.06
March	58,564	85,171	3,004,557	0.02
April	42,343	26,269	1,002,306	0.04
May	58,778	64,802	2,399,719	0.02
June	59,520	63,370	1,978,440	0.03
July	63,272	70,576	2,295,346	0.03
August	61,398	19,067	686,838	0.09
September	51,213	34,901	1,170,750	0.04
October	67,003	14,743	507,600	0.13
November	66,700	64,714	992,612	0.07
December	57,236	103,586	2,974,335	0.02
Average	**57,760**	**52,949**	**1,658,381**	**0.05**

$U=Sm*U_{sm}$ -- **Equation (4.4)**

Where,

U: Total number of electricity units used for chosen product

Sm: Number of standard allowed minutes for chosen product

U_{sm}: Number of electricity units per standard allowed minute

Using **Equation (4.4)**, the total number of electricity units per functional unit is calculated as follows:

Number of standard allowed minutes for chosen product (Source: Planning Dept.)	= 29.82
Number of electricity units per standard allowed minute	= 0.05
Total number of electricity units used for chosen product	= 29.82*0.05 kWh
	= **1.49 kWh**

4.5.4 Transportation

The emissions associated with transportation depend upon factors, such as the mode of transportation, the type of fuel, and engine efficiency. In this study, the emissions relevant for land transportation were calculated on the basis of the findings (emission factors) in the journal article, *Environmental assessment of international transportation of products* (Gerilla, Teknomo, & Hokao, 2005) where the calculation was based on Volvo F16 truck-transport in Gothenburg, Sweden. (The truck’s diesel engine runs on the Swedish MK-1 diesel. The energy content of this Swedish diesel is 9.77 kWh per litre while its sulphur content is 0.001% by weight) (refer to **Appendix E**).

R = {EF*FC*TU}/TC -- Equation (4.5)

Where,

R: Emission rate (measured in gram for 1 metre of fabric or 1 piece of garment to travel a distance of 1km)

EF: Emission factor

FC: Fuel consumption

TU: Truck utilisation

TC: Truck capacity

TE = R*D -- Equation (4.6)

Where,

TE: Total emission

R: Emission rate

D: Travel distance

Table 4.7 provides the calculation of emissions due to the transportation of fabrics from the port to the garment factory. In addition, the calculation of emissions associated with the garments’ transportation from the garment factory to the port is tabulated in Table 4.8, whereas the total emissions related to transportation are shown in Table 4.9.

Table 4.7: Emissions in transportation of fabrics from port to factory

Emission Elements	**CO_2**	**NO_x**	**SO_2**	**HC**	**PM**	**CO**
Emission Factor (g/litre)	2600.77	46.89	808.95	1.95	1.05	4.68
Fuel Consumption (litre/km)	0.05	0.05	0.05	0.05	0.05	0.05
Truck Capacity (in metre)	38,400	38,400	38,400	38,400	38,400	38,400
Truck Utilisation (%)	90	90	90	90	90	90
Emission Rate (g/1m of fabric per km)	3.04E-03	5.49E-05	9.48E-04	2.28E-06	1.23E-06	5.48E-06
Total Travel Distance (km)	171	171	171	171	171	171
Total Emissions (g/metre)	5.21E-01	9.40E-03	1.62E-01	3.90E-04	2.10E-04	9.38E-04
Fabric Consumption per Garment (m)	1.32	1.32	1.32	1.32	1.32	1.32
Total Emissions (g/garment)	**6.88E-01**	**1.24E-02**	**2.14E-01**	**5.16E-04**	**2.78E-04**	**1.23E-03**

Table 4.8: Emissions in transportation of garments from factory to port

Emission Elements	**CO_2**	**NO_x**	**SO_2**	**HC**	**PM**	**CO**
Emission Factor (g/litre)	2600.77	46.89	808.95	1.95	1.05	4.68
Fuel Consumption (litre/km)	0.05	0.05	0.05	0.05	0.05	0.05
Truck Capacity (Garment)	6,200	6,200	6,200	6,200	6,200	6,200
Truck Utilisation (%)	85	85	85	85	85	85
Emission Rate (g/1 garment per km)	1.78E-01	3.21E-04	5.54E-03	1.34E-05	7.20E-06	3.21E-05
Total Travel Distance (km)	171	171	171	171	171	171
Total Emissions (g/garment)	**3.05**	**5.50E-02**	**9.48E-01**	**2.28E-03**	**1.23E-03**	**5.49E-03**

Table 4.9: Total emissions in transportation

Emission Elements	**CO_2**	**NO_x**	**SO_2**	**HC**	**PM**	**CO**
Grand Total (g/garment)	**3.74**	**6.74E-02**	**1.16**	**2.80E-03**	**1.51E-03**	**6.72E-03**

The LCI of the garment manufacturing process was calculated by adding all of the associated inputs, outputs and emissions (see **Equation 4.7**). Table 4.10 shows LCI data of the garment manufacturing process, tabulated per one garment as well as per 1 kg of cotton.

$$\textbf{LCI (T)} = \sum \textbf{LCI (p)} \qquad \text{---} \ \textbf{Equation (4.7)}$$

Where,

LCI (T): LCI for the entire product system

LCI (p): LCI of process ***"p"***

Table 4.10: LCI for garment manufacturing

Element	Unit	LCI for Garment Manufacturing					
		Electricity			Transportation (per Garment)	Total (per Garment)	Total (per 1kg of Cotton) [1 Garment = 0.146kg of Cotton]
		Generation of 1kWh in Sri Lanka (Estimated)	Units (in kWh) per Garment	Per Garment [1kWh=3.6MJ]			
Energy consumption							
Electricity	**MJ**	**N.A.**	**1.49**	**5.36E+00**	**N.D.**	**5.36E+00**	**3.67E+01**
Fossil fuel	**MJ**	**N.A.**	**1.49**	**–**	**N.D.**	**–**	**–**
Non-renewable resources							
Natural gas	**kg**	**1.50E-03**	**1.49**	**2.23E-03**	**–**	**2.23E-03**	**1.53E-02**
Crude oil	**kg**	**2.34E-03**	**1.49**	**3.49E-03**	**–**	**3.49E-03**	**2.39E-02**
Coal	**kg**	**3.40E-01**	**1.49**	**5.07E-01**	**–**	**5.07E-01**	**3.47E+00**
LP gas	**kg**	**1.12E-02**	**1.49**	**1.67E-02**	**–**	**1.67E-02**	**1.15E-01**
Water	**kg**	**4.32E-01**	**1.49**	**6.44E-01**	**–**	**6.44E-01**	**4.41E+00**
Fertilisers	**g**	**N.D.**	**1.49**	**N.D.**	**–**	**–**	**–**
Pesticides	**g**	**N.D.**	**1.49**	**N.D.**	**–**	**–**	**–**
Detergents	**g**	**N.D.**	**1.49**	**N.D.**	**–**	**–**	**–**
Emissions to air							
CO_2	**kg**	**6.88E-01**	**1.49**	**1.03E+00**	**3.74E-03**	**1.03E+00**	**7.08E+00**
CH_4	**kg**	**7.51E-06**	**1.49**	**1.12E-05**	**N.D.**	**1.12E-05**	**7.67E-05**
SO_2	**kg**	**1.07E-05**	**1.49**	**1.59E-05**	**1.16E-03**	**1.18E-03**	**8.05E-03**
NOx	**kg**	**3.12E-05**	**1.49**	**4.65E-05**	**6.74E-05**	**1.14E-04**	**7.80E-04**
CH	**kg**	**3.85E-03**	**1.49**	**5.74E-03**	**2.80E-06**	**5.74E-03**	**3.93E-02**
CO	**kg**	**7.93E-04**	**1.49**	**1.18E-03**	**6.72E-06**	**1.19E-03**	**8.13E-03**
N_2O	**kg**	**1.07E-05**	**1.49**	**1.59E-05**	**N.D.**	**1.59E-05**	**1.09E-04**
NMVOC	**kg**	**1.78E-04**	**1.49**	**2.65E-04**	**N.D.**	**2.65E-04**	**1.81E-03**
PM	**kg**	**3.21E-02**	**1.49**	**4.79E-02**	**1.51E-06**	**4.79E-02**	**3.28E-01**
Emissions to water							
COD	**g**	**N.D.**	**1.49**	**–**	**N.D.**	**–**	**–**
BOD	**g**	**N.D.**	**1.49**	**–**	**N.D.**	**–**	**–**
Tot-P	**g**	**N.D.**	**1.49**	**–**	**N.D.**	**–**	**–**
Tot-N	**g**	**N.D.**	**1.49**	**–**	**N.D.**	**–**	**–**

Assumption:
1. Dust and coal fly ash are taken as PM
2. Coke oven gas and other gas mentioned in Table 4.5, are taken as LP gas
3. Conversion factor of natural gas, $1m^3$=0.714kg
4. Conversion factor of LP gas (in gaseous form), $1m^3$=2.05kg

N.A. – Not applicable
N.D. – No data

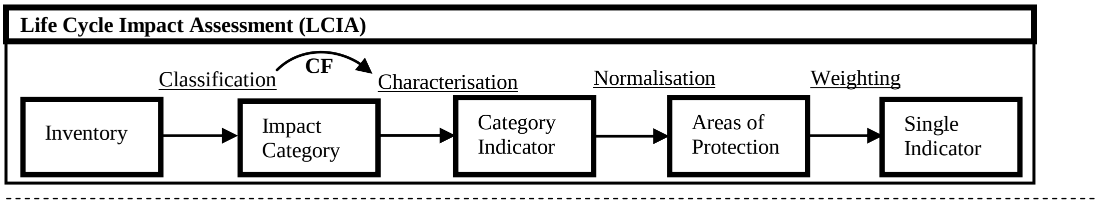
4.5.5 Fibre-to-Fashion

Similarly, the LCI for Fibre-to-Fashion was calculated (see Table 4.11). The data relevant for fibre production, fabric (including yarn) production and laundry were obtained from Kalliala and Nousiainen’s (1999) “Life Cycle Assessment - Environmental profile of cotton and polyester-cotton” and Kalliala’s (n.d.) “The environmental index model for textiles and textile services” (refer to **Annex F**).

Table 4.11: LCI

Element	Unit	Fibre Production	Fibre and Fabric (including yarn) Production	Garment Production	Laundry	Total (Fibre-to-Fashion)	Total (Fibre-to-Fashion)
		Per 1 kg of Cotton					Per 1 Garment [1 Garment =0.146 kg of Cotton]
Energy consumption							
Electricity	**MJ**	**1.21E+01**	**3.46E+01**	**3.67E+01**	**9.40E-01**	**7.22E+01**	**1.05E+01**
Fossil fuel	**MJ**	**4.77E+01**	**5.98E+01**	**–**	**6.76E+00**	**6.66E+01**	**9.72E+00**
Non-renewable resources							
Natural gas	**kg**	**3.50E-01**	**6.20E-01**	**1.53E-02**	**1.57E+02**	**1.58E+02**	**2.30E+01**
Crude oil	**kg**	**5.30E-01**	**6.70E-01**	**2.39E-02**	**2.00E+00**	**2.69E+00**	**3.93E-01**
Coal	**kg**	**5.20E-01**	**9.20E-01**	**3.47E+00**	**1.40E+01**	**1.84E+01**	**2.68E+00**
LP gas	**kg**	**3.00E-02**	**4.00E-02**	**1.15E-01**	**N.D.**	**1.55E-01**	**2.26E-02**
Water	**kg**	**2.22E+04**	**2.61E+04**	**–**	**1.60E+01**	**2.61E+04**	**3.81E+03**
Fertilisers	**g**	**4.57E+02**	**5.37E+02**	**–**	**–**	**5.37E+02**	**7.84E+01**
Pesticides	**g**	**1.60E+01**	**1.89E+01**	**–**	**–**	**1.89E+01**	**2.76E+00**
Detergents	**g**	**–**	**–**	**–**	**1.26E+01**	**1.26E+01**	**1.84E+00**
Emissions to air							
CO_2	**kg**	**4.27E+00**	**6.55E+00**	**7.08E+00**	**4.90E-04**	**1.36E+01**	**1.99E+00**
CH_4	**kg**	**7.60E-03**	**1.30E-02**	**7.67E-05**	**1.42E-03**	**1.45E-02**	**2.12E-03**
SO_2	**kg**	**4.00E-03**	**6.30E-03**	**8.05E-03**	**9.00E-05**	**1.44E-02**	**2.11E-03**
NO_x	**kg**	**2.27E-02**	**3.02E-02**	**7.80E-04**	**1.30E-03**	**3.23E-02**	**4.17E-03**
CH	**kg**	**5.00E-03**	**6.90E-03**	**3.93E-02**	**7.00E-05**	**4.63E-02**	**6.76E-03**
CO	**kg**	**1.61E-02**	**2.82E-02**	**8.13E-03**	**5.00E-04**	**3.68E-02**	**5.38E-03**
N_2O	**kg**	**–**	**–**	**1.09E-04**	**–**	**1.09E-04**	**1.59E-05**
NMVOC	**kg**	**–**	**–**	**1.81E-03**	**–**	**1.81E-03**	**2.64E-03**
PM	**kg**	**–**	**–**	**3.28E-01**	**–**	**3.28E-01**	**4.79E-02**
Emissions to water							
COD	**kg**	**N.D.**	**1.33E+01**	**–**	**1.20E+00**	**1.45E+01**	**2.12E+00**
BOD	**kg**	**N.D.**	**5.10E+00**	**–**	**6.40E+00**	**1.15E+01**	**1.68E+00**
Tot-P	**kg**	**N.D.**	**5.20E-02**	**–**	**5.00E-02**	**1.02E-01**	**1.49E-02**
Tot-N	**kg**	**N.D.**	**4.00E-02**	**–**	**1.30E-01**	**1.70E-01**	**2.48E-02**

4.6 Life Cycle Impact Assessment



In this study, the calculations were effected up to the point of *characterisation*. The *normalisation* and *weighting* were not considered due to the traits' highly subjective natures.

4.6.1 Classification

The classification was made based on *CMLCA*, as published by the Institute of Environmental Sciences (2013) in its software (refer to **Appendix G**).

4.6.2 Characterisation factors

The Institute of Environmental Sciences' (2013) characterisation factors, published in its software, were used in this study. Similar data can be found in Dutch LCA Guide (VROM & CML, 2001) (see Table 4.12).

Table 4.12: Characterisation factors

Element	Unit	LCI	Impact Category					
			Global Warming, GWP100 (IPCC, 2007)	Photochemical Oxidation	Ozone Layer Depletion	Acidification	Eutrophication	Abiotic Depletion
			kg CO_2-eq.	kg C_2H_4 -eq.	kg CFC11-eq.	kg SO_2-eq.	kg PO_4-eq.	MJ
Energy consumption								
Electricity	**MJ**	**1.05E+01**						**1.00E+00**
Fossil fuel	**MJ**	**9.72E+00**						**1.00E+00**
Non-renewable resources								
Natural gas	**kg**	**2.30E+01**						**3.88E+01**
Crude oil	**kg**	**3.93E-01**						**4.19E+01**
Coal	**kg**	**2.68E+00**						**2.79E+01**
LP gas	**kg**	**2.26E-02**						**1.00E+00**
Water	**kg**	**3.81E+03**						**1.00E+00**
Fertilisers	**g**	**7.84E+01**						
Pesticides	**g**	**2.76E+00**						
Detergents	**g**	**1.84E+00**						
Emissions to air								
CO_2	**kg**	**1.99E+00**	**1.00E+00**					
CH_4	**kg**	**2.12E-03**	**2.50E+01**	**6.00E-03**				
SO_2	**kg**	**2.11E-03**		**4.80E-02**		**1.20E+00**		
NO_x	**kg**	**4.17E-03**		**2.80E-02**		**5.00E-01**	**1.30E-01**	
CH	**kg**	**6.76E-03**						
CO	**kg**	**5.38E-03**	**1.00E+00**	**2.70E-02**				
N_2O	**kg**	**1.59E-05**	**3.10E+02**					
NMVOC	**kg**	**2.64E-03**	**4.50E-02**	**1.50E-01**	**2.30E-05**			
PM	**kg**	**4.79E-02**						
Emissions to water								
COD	**kg**	**2.12E+00**					**2.20E-02**	
BOD	**kg**	**1.68E+00**						
Tot-P	**kg**	**1.49E-02**					**1.00E+00**	
Tot-N	**kg**	**2.48E-02**					**4.20E-01**	

Assumption:

1. The characterisation factors of “LP gas” & “Water” for “Abiotic depletion” were assumed as 1.
2. The characterisation factor of “N_2O” was obtained from the characterisation model developed by the Intergovernmental Panel on Climate Change (IPCC) (Bengtsson & Howard, 2010).

4.6.3 Characterisation

$$\textbf{Impact (I)} = \sum \textbf{LCI (v)*CF (v)} \qquad \text{-------------------------------------} \quad \textbf{Equation (4.8)}$$

Where,

Impact (I): Impact category

LCI (v): LCI value of element ***“v”***

CF (v): Characterisation factor of element ***“v”***

With reference to **Equation (4.8)**, the characterisation was performed (it was assumed that LCI elements could be apportioned using the parallel mechanism). The results are shown in Table 4.13.

Table 4.13: Characterisation

Element	Unit	LCI	Climate Change (kg CO_2-eq.)	Photochemical Formation (kg C_2H_4-eq.)	Ozone Layer Depletion (kg CFC11-eq.)	Acidification (kg SO_2-eq.)	Eutrophication (kg PO_4-eq.)	Resource Depletion (MJ/ Water is in kg)
		Per garment (1 piece)						
Energy consumption								
Electricity	**MJ**	**1.05E+01**						**1.05E+01**
Fossil fuel	**MJ**	**9.72E+00**						**9.72E+00**
Non-renewable resources								
Natural gas	**kg**	**2.30E+01**						**8.92E+02**
Crude oil	**kg**	**3.93E-01**						**1.65E+01**
Coal	**kg**	**2.68E+00**						**7.48E+01**
LP gas	**kg**	**2.26E-02**						**2.26E-02**
Water	**kg**	**3.81E+03**						**3.81E+03**
Fertilisers	**g**	**7.84E+01**						
Pesticides	**g**	**2.76E+00**						
Detergents	**g**	**1.84E+00**						
Emissions to air								
CO_2	**kg**	**1.99E+00**	**1.99E+00**					
CH_4	**kg**	**2.12E-03**	**2.65E-02**	**6.36E-06**				
SO_2	**kg**	**2.11E-03**		**5.06E-05**		**1.27E-03**		
NO_x	**kg**	**4.17E-03**		**3.89E-05**		**6.95E-04**	**1.81E-04**	
CH	**kg**	**6.76E-03**						
CO	**kg**	**5.38E-03**	**2.69E-03**	**7.26E-05**				
N_2O	**kg**	**1.59E-05**	**4.93E-03**					
NMVOC	**kg**	**2.64E-03**	**3.96E-05**	**1.32E-04**	**2.02E-08**			
PM	**kg**	**4.79E-02**						
Emissions to water								
COD	**kg**	**2.12E+00**					**4.66E-02**	
BOD	**kg**	**1.68E+00**						
Tot-P	**kg**	**1.49E-02**					**1.49E-02**	
Tot-N	**kg**	**2.48E-02**					**1.04E-02**	
Total			**2.02E+00**	**3.01E-04**	**2.02E-08**	**1.96E-03**	**7.21E-02**	**Refer to 4.7**

4.7 Improvement Analysis

Improvement Analysis	
-	Interpret results

As per the LCI analysis, the consumption of water reaches 3.81×10^3 kg per one cotton blouse during its life cycle. The total water consumption for the use phase (activity: laundry) was taken as 16 kg, as found in Kalliala and Nousiainen's (1999) study. The latter might be seen as an underestimation when considering the real-life scenario of the cotton-blouse. However, the actual consumption of water during the use phase depends on both the consumer behaviour (e.g., total number of wears during use, number of wears between each wash) and the product's care instructions. Ultimately, waterless fabric dyeing/finishing and easy care fabric finishes are factors for consideration, since the water demand in the cotton plantation is not a straightforward factor that can be manipulated for reducing the water consumption. (1 kg of water is equivalent to 1 litre of water.)

The usage of fertiliser and pesticides can be limited through the promotion of organic or BCI cotton, where the cotton plantation is handled through more sustainable means. However, the organic cotton concept has not yet been very successful due to its inherent limitations on the production of defect-free fabrics, especially in finer counts. Therefore, genetically modified cotton may be the answer.

The values of the LCI elements were apportioned equally among the impact categories for which the respective element might have had a possible impact. However, the allocation in real-life might be different, depending on various environmental factors. In this study, the normalisation and weighting were not performed due to the subjective nature of the methodology. Therefore, the total environmental impact was not expressed as a single value.

The toxicological stress on human health and the eco-system due to chemicals, which are largely used during the fabric production stage, is currently in the global spotlight partly due to the "Detox campaign," which has the goal of achieving "Zero Discharge of Hazardous Chemicals by 2020". However, this can be seen as a very challenging task due to incomplete databases and unpublished data regarding industrial chemicals.

The CO_2 emissions might be partly offset due to photosynthesis during cotton farming. Any surplus will challenge the global climate patterns since greenhouse gases, such as CO_2, have a longer lifetime in the atmosphere. In the interim, the 100-year time scale can be proposed as being suitable for analysis.

The values under the impact category “Resource Depletion” were not added together due to the heterogeneity of the elements (expressed in different units) involved. In addition, fertilisers, pesticides, detergents, CH (hydrocarbons), PM (particular matters) and BOD (biochemical oxygen demand) were not allocated for any of the impact categories chosen for this study.

Chapter 5

DISCUSSION, CONCLUSIONS AND FUTURE WORK

Discussion

The literature review demonstrated that there is an extensive amount of studies relevant to life cycle assessment, which is a powerful tool for quantifying, evaluating, comparing, and improving products and services in terms of their potential environmental impact. Thus, to drive towards the sustainability, life cycle assessment is an essential part of most organisations' sustainability plans. However, current references rarely include complete environmental, economic and social impact estimates.

LCA is, as far as possible, quantitative in nature. Where this is not possible, qualitative aspects can and should be taken into account so that as complete a picture as possible can be given regarding the potential environmental impacts involved (VROM & CML, 2001). In LCA, the difficulties and uncertainties in data collection and analysis remain challenging. This is partly due to the geographically dependent nature of the products and process, whereby each country has to generate its own data. Second, the data have to be combined from different references available in scattered sources, where various assumptions are normally incorporated. Third, the technological advancements make historical data redundant, requiring new data to be gathered. Hence, quantifying the overall uncertainties of indicator results and establishing how to account for such uncertainties in the decision-making process are desirable. The fuzzy representation of preferences, according to indifference and preference thresholds, in order to reduce the uncertainty related to the life cycle impact assessment results due to the uncertainties of the life cycle inventory, needs to be explored (Benetto, Dujet, & Rousseaux, 2008).

At present, life cycle assessments are mainly confined to inventory analysis, which quantifies resource inputs and environmental outputs where elements reaching a minimum percentage of the total mass are considered for further evaluation. Within such inventory analyses, most of the attention is focused on the estimation of primary energy inputs, measuring primarily fossil fuel depletion and greenhouse gas emissions (mainly carbon dioxide, methane and nitrous oxide) that are related to global climate change. Some studies present a complete inventory analysis and extend as far as the classification, characterisation and interpretation phases. However, full coverage in this depth of all relevant technologies is not currently available.

Simplification of LCI can help to avoid complexities and the time-consuming nature of life cycle assessment, providing veritable means of achieving objectives through a narrow domain. The primary issues of process-life cycle assessment are the need to establish boundary limits and the circulatory effect (i.e., interdependency of two products over the other in a cyclic manner.) The former is carried out to make the life cycle assessment study feasible in terms of data collection. However, this automatically limits the results and creates an underestimate of the true life cycle impacts. The circulatory effect creates the need for completing a life cycle assessment of all materials and processes before one can complete a life cycle assessment of any material or process. These two issues are eliminated by the use of an economic input-output life cycle assessment, where aggregate sector-level data are used.

The hybrid-life cycle assessment method allows for life cycle assessments with incomplete information, enabling the creation of models that significantly reduce the truncation error inherent in process-life cycle assessment, while preserving process specificity with relatively small amounts of additional information and inventory data (Heinonen & Junnila, 2011). By iterating the procedure, an LCA practitioner can achieve both higher level of completeness and accuracy (Rebitzer et al., 2004).

In LCAs, the impacts do not specify time and space related to a functional unit, nor do they address localised effects. However, it is possible to scale down some of the results in order to identify the regions where certain emissions take place, after which, differences in the sensitivity of these regions can be taken into account in the LCA context (VROM & CML, 2001). Furthermore, the transparency is an important aspect when executing an LCA due to its inherent complexity in cases when comparing the results of different LCA studies is not otherwise feasible.

Conclusions

As the case study results were quite comparable, the proposed Fibre-to-Fashion LCA methodology can be used to analyse environmental performance of apparel products in the global context. The case study showed electricity consumption as a key factor for potential environmental impacts during apparel manufacturing. Therefore, high productivity in the apparel sector could assist not only in gaining higher profits, but also in achieving a higher level of sustainability. In practical terms, the boundaries of LCA application can vary significantly accordingly to context and conditions. Furthermore, the higher degree of accuracy can be achieved only through accurate modelling and data gathering. LCA supports the identification of opportunities for pollution prevention and for the reduction of resource consumption through systematic analysis. New emerging cleaner technologies are in a key position when striving towards zero discharge of hazardous chemicals in textile processing, and the application of LCAs to develop ecological impact indicators is vital.

Future Work

There is a limitation to the extent of which the impacts on human health, the ecosystem and natural resources can be modelled to map real-life scenarios. However, credible science-based endpoint methods (damage effect indicating methods) need to be further explored. Moreover, LCA does not provide the framework for a complete local risk assessment study, i.e., identifying which impacts can be expected due to the functioning of a product system in a specific locality. Therefore, new research is required to establish impact models that are compatible for different spacial boundaries. In addition, easily accessible tools and appropriate international databases are important for the global proliferation of LCA.

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Appendix

Appendix A: Impact Categories and Characterisation Factors (SAIC, 2006)

Impact Category	**Scale**	**Examples of LCI Data (i.e., classification)**	**Common Possible Characterisation Factor**	**Description of Characterisation Factor**
Global Warming	Global	Carbon Dioxide (CO_2) Nitrogen Dioxide (NO_2) Methane (CH_4) Chlorofluorocarbons (CFCs) Hydrochlorofluorocarbons (HCFCs) Methyl Bromide (CH_3Br)	Global Warming Potential	Converts LCI data to carbon dioxide (CO_2) equivalents Note: Global warming potentials can be 50, 100, or 500 year potentials.
Stratospheric Ozone Depletion	Global	Chlorofluorocarbons (CFCs) Hydrochlorofluorocarbons (HCFCs) Halons Methyl Bromide (CH_3Br)	Ozone Depleting Potential	Converts LCI data to trichlorofluoromethane (CFC-11) equivalents.
Acidification	Regional Local	Sulphur Oxides (SO_x) Nitrogen Oxides (NO_x) Hydrochloric Acid (HCL) Hydrofluoric Acid (HF) Ammonia (NH_4)	Acidification Potential	Converts LCI data to hydrogen (H+) ion equivalents.
Eutrophication	Local	Phosphate (PO_4) Nitrogen Oxide (NO) Nitrogen Dioxide (NO_2) Nitrates Ammonia (NH_4)	Eutrophication Potential	Converts LCI data to phosphate (PO_4) equivalents.
Photochemical Smog	Local	Non-methane hydrocarbon (NMHC)	Photochemical Oxidant Creation Potential	Converts LCI data to ethane (C_2H_6) equivalents.
Terrestrial Toxicity	Local	Toxic chemicals with a reported lethal concentration to rodents	LC50	Converts LC50 data to equivalents; uses multi-media modelling, exposure pathways.
Aquatic Toxicity	Local	Toxic chemicals with a reported lethal concentration to fish	LC50	Converts LC50 data to equivalents; uses multi-media modelling, exposure pathways.
Human Health	Global Regional Local	Total releases to air, water, and soil.	LC50	Converts LC50 data to equivalents; uses multi-media modelling, exposure pathways.
Resource Depletion	Global Regional Local	Quantity of minerals used Quantity of fossil fuels used	Resource Depletion Potential	Converts LCI data to a ratio of quantity of resource used versus quantity of resource left in reserve.
Land Use	Global Regional Local	Quantity disposed of in a landfill or other land modifications	Land Availability	Converts mass of solid waste into volume using an estimated density.
Water Use	Regional Local	Water used or consumed	Water Shortage Potential	Converts LCI data to a ratio of quantity of water used versus quantity of resource left in reserve.

Appendix B: Life Cycle Inventory of Thermal Power Generation for 1kWh Electricity Generation for 2007 in China (Sha et al., 2012)

		Unit	Consumption/ Emission
Fossil fuel	**Raw coal**	**kg**	**4.80E-01**
	Crude oil	**kg**	**3.31E-03**
	Natural gas	**m^3**	**2.96E-03**
	Coke oven gas	**m^3**	**2.92E-03**
	Other gas	**m^3**	**4.81E-03**
Pollutants	**CO_2**	**kg**	**9.70E-01**
	CH_4	**kg**	**1.06E-05**
	N_2O	**kg**	**1.51E-05**
	SO_2	**kg**	**4.41E-03**
	NO_2	**kg**	**5.44E-03**
	CO	**kg**	**1.12E-03**
	NMVOC	**kg**	**2.52E-04**
	Dust	**kg**	**1.30E-03**
	Industry water	**kg**	**6.10E-01**
	Coal fly ash	**kg**	**4.41E-02**

Appendix C: A Life Cycle Analysis of Electricity Generation Technologies (Bergerson & Lave, 2002)

Total Lifetime GWP for Various Fuels/Technologies					
	Hydroelectric	Photovoltaic	Wind Farm	Coal	Natural Gas
Output (TWh)	5.55	5.55	5.55	5.55	5.55
Emissions (MT CO_2 equiv.)					
CO_2 (x 10^6)	5.10E-01	1.10E+00	8.20E-01	8.6E+01	5.1E+01
CH_4 (x 10^4)	8.40E-02	7.80E-01	5.40E-02	3.5E+01	5.0E+01
N_2O (x 10^4)	8.50E-01	8.70E+00	6.50E-01	2.20E+02	2.20E+02
GWE (x 10^6)	5.10E-01	1.10E+00	8.30E-01	8.6E+01	5.40E+01

Appendix D: Environmental Assessment of International Transportation of Products (Gerilla et al., 2005)

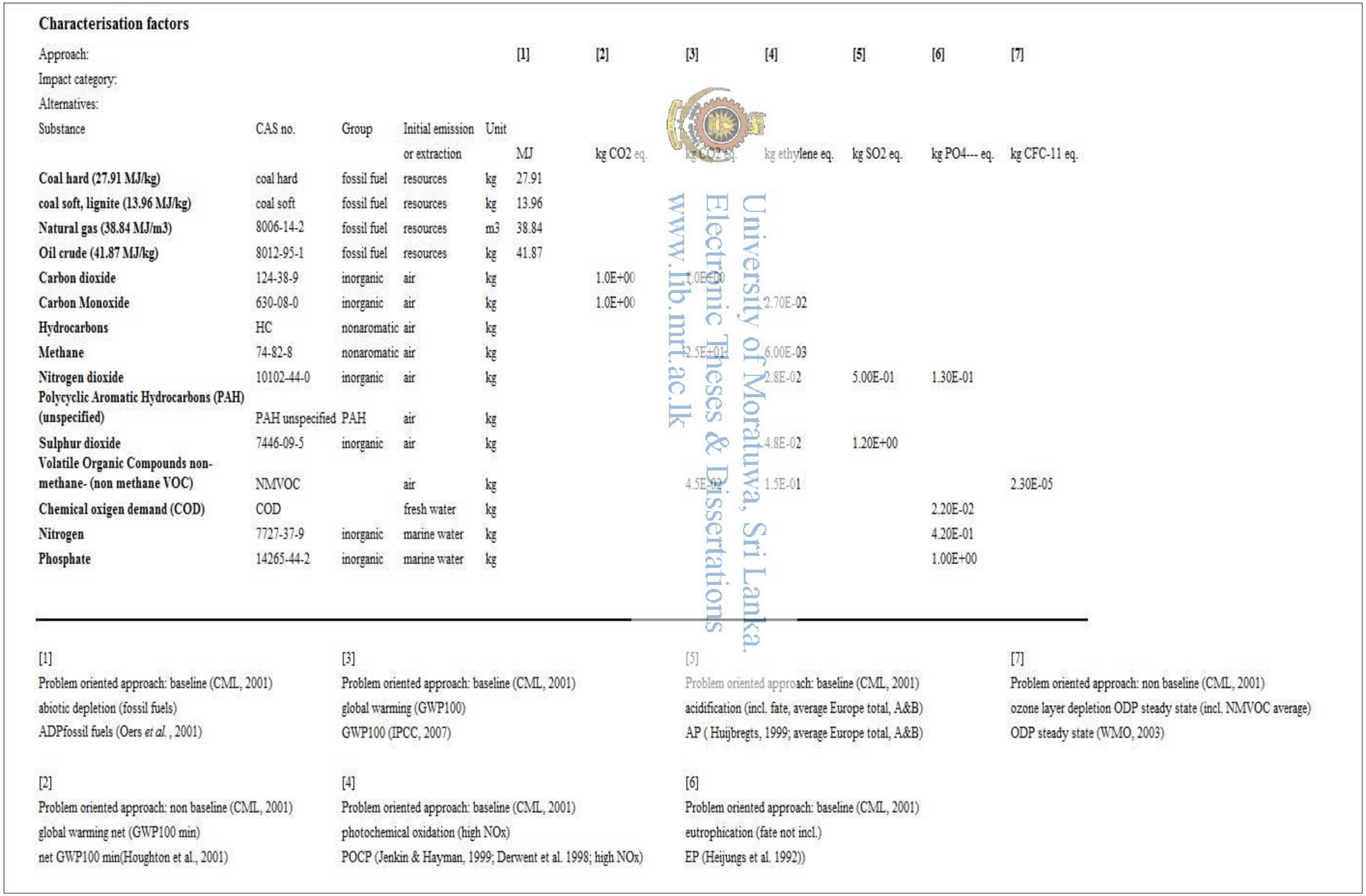
Emission element	**CO_2**	**NO_x**	**SO_2**	**HC**	**PM**	**CO**
Energy of engine: (gram/kWh) 1	**665.5**	**12**	**207**	**0.5**	**0.27**	**1.2**
Efficiency of engine: (%)	**40**	**40**	**40**	**40**	**40**	**40**
Conversion to fuel: (grams/kWh(fuel)	**266.2**	**4.8**	**82.8**	**0.2**	**0.108**	**0.48**
Energy content of fuel: (kWh/litre)	**9.77**	**4.8**	**9.77**	**9.77**	**9.77**	**9.77**
Emission factors: (grams/litre)	**2600.77**	**46.89**	**808.95**	**1.95**	**1.05**	**4.68**

(The emission factor for truck transport in Gothenburg)

Appendix E: Life Cycle Assessment – Environmental Profile of Cotton and Polyester-cotton (Kalliala & Nousiainen, 1999) and The Environmental Index Model for Textiles and Textile Services (Kalliala, n.d.)

Parameter	**Unit**	**Fibre Production**	**Fibre and Fabric Production**	**Laundry**
		Cotton (kg)		
Energy Consumption	**MJ**	**5.98E+01**	**9.93E+01**	**7.70E+00**
Electricity	MJ	1.21E+01	3.46E+01	9.40E-01
Fossil fuel	MJ	4.77E+01	5.98E+01	6.76E+00
Others	MJ	–	4.90E+01	2.30E-07
Non-renewable resources	**kg**	**1.40E+00**	**2.20E+01**	**2.00E-01**
Natural gas	**kg**	**3.50E-01**	**6.20E-01**	**1.57E+02**
Crude oil	**kg**	**5.30E-01**	**6.70E-01**	**2.00E+00**
Coal	**kg**	**5.20E-01**	**9.20E-01**	**1.40E+01**
LP gas	**kg**	**3.00E-02**	**4.00E-02**	–
Hydro power	**MJ**	**1.00E+00**	**5.80E+00**	**2.10E-01**
Natural uranium	**Mg**	**1.40E+01**	**5.54E+01**	**1.80E+00**
Fertilisers	**g**	**4.57E+02**	**5.37E+02**	–
Pesticides	**g**	**1.60E+01**	**1.89E+01**	–
Water	**kg**	**2.22E+04**	**2.61E+04**	**1.60E+01**
Detergents	**g**	–	–	**1.26E+01**
Emissions to air				
CO_2	**kg**	**4.27E+00**	**6.55E+00**	**4.90E-04**
CH_4	**kg**	**7.60E-03**	**1.30E-02**	**1.42E-03**
SO_2	**kg**	**4.00E-03**	**6.30E-03**	**9.00E-05**
NO_x	**kg**	**2.27E-02**	**3.02E-02**	**1.30E-03**
CH	**kg**	**5.00E-03**	**6.90E-03**	**7.00E-05**
CO	**kg**	**1.61E-02**	**2.82E-02**	**5.00E-04**
PM	**kg**	–	–	–
Emissions to water				
COD	**kg**	–	**1.33E+01**	**1.20E+00**
BOD	**kg**	–	**5.10E+00**	**6.40E+00**
Tot-P	**kg**	–	**5.20E-02**	**5.00E-02**
Tot-N	**kg**	–	**4.00E-02**	**1.30E-01**

Appendix F: Abstract of Characterisation Factors Published by the Institute of Environmental Sciences (2013)



Characterisation factors

Approach:					[1]	[2]	[3]	[4]	[5]	[6]	[7]
Impact category:											
Alternatives:											
Substance	CAS no.	Group	Initial emission or extraction	Unit	MJ	kg CO2 eq.	kg CO2 eq.	kg ethylene eq.	kg SO2 eq.	kg PO4--- eq.	kg CFC-11 eq.
Coal hard (27.91 MJ/kg)	coal hard	fossil fuel	resources	kg	27.91						
coal soft, lignite (13.96 MJ/kg)	coal soft	fossil fuel	resources	kg	13.96						
Natural gas (38.84 MJ/m3)	8006-14-2	fossil fuel	resources	m3	38.84						
Oil crude (41.87 MJ/kg)	8012-95-1	fossil fuel	resources	kg	41.87						
Carbon dioxide	124-38-9	inorganic	air	kg		1.0E+00	1.0E+00				
Carbon Monoxide	630-08-0	inorganic	air	kg		1.0E+00		2.70E-02			
Hydrocarbons	HC	nonaromatic	air	kg							
Methane	74-82-8	nonaromatic	air	kg			2.5E+01	6.00E-03			
Nitrogen dioxide	10102-44-0	inorganic	air	kg				2.8E-02	5.00E-01	1.30E-01	
Polycyclic Aromatic Hydrocarbons (PAH) (unspecified)	PAH unspecified	PAH	air	kg							
Sulphur dioxide	7446-09-5	inorganic	air	kg				4.8E-02	1.20E+00		
Volatile Organic Compounds non-methane- (non methane VOC)	NMVOC		air	kg			4.5E-02	1.5E-01			2.30E-05
Chemical oxigen demand (COD)	COD		fresh water	kg						2.20E-02	
Nitrogen	7727-37-9	inorganic	marine water	kg						4.20E-01	
Phosphate	14265-44-2	inorganic	marine water	kg						1.00E+00	

[1]
Problem oriented approach: baseline (CML, 2001)
abiotic depletion (fossil fuels)
ADPfossil fuels (Oers *et al.*, 2001)

[2]
Problem oriented approach: non baseline (CML, 2001)
global warming net (GWP100 min)
net GWP100 min(Houghton et al., 2001)

[3]
Problem oriented approach: baseline (CML, 2001)
global warming (GWP100)
GWP100 (IPCC, 2007)

[4]
Problem oriented approach: baseline (CML, 2001)
photochemical oxidation (high NOx)
POCP (Jenkin & Hayman, 1999; Derwent et al. 1998; high NOx)

[5]
Problem oriented approach: baseline (CML, 2001)
acidification (incl. fate, average Europe total, A&B)
AP (Huijbregts, 1999; average Europe total, A&B)

[6]
Problem oriented approach: baseline (CML, 2001)
eutrophication (fate not incl.)
EP (Heijungs et al. 1992))

[7]
Problem oriented approach: non baseline (CML, 2001)
ozone layer depletion ODP steady state (incl. NMVOC average)
ODP steady state (WMO, 2003)