Enhancing Product Sustainability with Life Cycle Assessment and Relevant Technologies

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Abstract

Promoting sustainable products and resource efficiency have become two major policy objectives in Europe, and resource efficiency has become an important political objective on the agenda of the European Commission. Life Cycle Assessment (LCA) acts as an efficient framework to evaluate product environmental performances and improve resource efficiency.

An integrated approach implemented by three ICT systems are developed to support sustainable production. A sustainable production support toolbox has been developed that contains state-of-art tools regarding LCA software and database tools, environmental management schemes, the EU regulations and directives and stands associated with sustainable production. The applicable requirements, scope and advantages have been examined to develop the tools selection considerations. Compared with the existing toolbox, the distinguished novelty of the developed toolbox is that it can integrate into the product development process, the feasibility and utility of which has been demonstrated by reporting a sustainable flooring product development process.

A framework for converting the existing ecoinvent database into a SQL supported database has also been developed, in order to use the ecoinvent database to serve web applications. The data format (i.e. EcoSpold) of the ecoinvent database is a custom XML format, and Python XML processing library has been applied to employ SAX approach to extract the massive data values and information from the EcoSpold files. The demonstrated framework

and adopted approaches successfully convert the ecoinvent database into a SQL database management tool. Moreover, a Java GUI application has been developed to invoke the SQL based LCI database and the aggregated LCI datasets from the web-based product environmental assessment system.

A web-based product environmental performance assessment system has been developed to achieve powerful, flexible and efficient online LCA calculations, by converting a desktop LCA software and applying a High-Performance Calculation Library. Moreover, a mobile client application has been developed to help consumers to evaluate purchased products sustainability performance and implement sustainable consumption. This developed tool is a novel web system that can perform powerful web and mobile based LCA calculations. The performance of the web system has been examined by applying a LCA on the shampoo product.

A dedicated LCA on shampoo product has been conducted by using the SimaPro. The LCI datasets are provided by its manufacturer, a UK based company, and also fulfilled by applying ecoinvent database. This case study presents an in-depth modelling and analysis on shampoo product lifecycle with the aid of real manufacturing data. The analytical results also show that the lifecycle stage of major environmental impacts is in the shampoo utilisation stages.

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Nomenclature

API: Application Programming Interface

BAT: Best Available Techniques

CAD: Computer Aided Design

CML: Institute of Environmental Sciences

CSS: Cascading Style Sheets

DEFRA: Department for Environment, Food & Rural Affairs

DfE: Design for Environment

EEE: Electrical and Electronic Equipment

ELCD: European Reference Life Cycle Database

EMAS: Eco-management and Audit Scheme

EMS: Environmental Management Scheme

EoF: End of Life

ERP: Enterprise Resource Planning

FEA: Finite Element Analysis

FMEA: Failure Mode and Effect Analysis

GHG: Greenhouse Gases

GIS: Geographic Information System

GUI: Graphical User Interface

GWP: Global Warming Potential

HTML: Hypertext Markup Language

HTTP: Hypertext Transfer Protocol

HMI: Human Machine Interface

ILCD: International Reference Life Cycle Data System

JNI: Java Native Interface

JSON: JavaScript Object Notation

JVM: Java Virtual Machine

ICT: Information and Communication Technology

ISO: International Organization for Standardization

LCA: Life Cycle Assessment

LCC: Life Cycle Costing

LCE: Life Cycle Engineering

LCI: Life Cycle Inventory

LCS: Life Cycle Sustainability

LCIA: Life Cycle Impact Assessment

MEFA: Material Energy Flow Analysis

PDS: Product Design Specifications

PEF: Product Environmental Footprint

PET: Polyethylene Terephthalate

PVC: Polyvinyl Chloride

RAP: Remote Application Platform

RCP: Rich Client Platform

SWT: Standard Widget Toolkit

SMC: Sheet Moulding Compound

SOA: Service Oriented Architecture

SOAP: Simple Object Access Protocol

SQL: Structured Query Language

TCP: Transformation Control Protocol

UDDI: Universal Description, Discovery, and Integration

UDP: User Datagram Protocol

WEEE: Waste Electrical and Electronic Equipment

WFLDB: World Food LCA database

WSDL: Web Service Description Language

XML: Extensible Markup Language

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Chapter 1: Introduction

1.1. Research background

The need for a transition of economy towards more sustainability is widely accepted in our society. This includes the reduction of material use (UNEP 2014) and carbon emissions (IPCC 2014) in production and consumption. In Europe, promoting green products and resource efficiency have become two major policy objectives, and resource efficiency has become an important political objective on the agenda of the European Commission (EEA 2012). An important opinion suggested by the "Europe 2020" strategy is to lay out a vision that in the future all companies should be able to measure and benchmark their resource efficiency (Galli et al. 2012). Furthermore, the Product Environmental Footprint (PEF) initiative refers to one of the most common methods to quantify environmental impacts, known as Life Cycle Assessment (LCA) (ISO 2006a).

Such a demand requests the products to have sustainable features not only at the product function level, such as low power consumption and easy to reuse/recycling, but also through various stages within the product supply chain, such as material extraction, production, transportation, etc. (Cambero & Sowlati 2014).The findings of this research show that LCA is an efficient tool that is widely adopted by the actors in the supply chain and value chain, in order to evaluate environmental performance and identify pollution roots. However, the complexity of global production systems and limited availability and quality of life cycle data are two main barriers to such a transition (UNEP 2012). Despite this awareness and a theoretical understanding of what is needed, improving availability and quality of life cycle data are also huge challenges.

Within the context of pursuing sustainable production, attempts have been made to apply sustainability enhancement tools in product design and production, for example, Bovea & Pérez-Belis examined the main eco-design tools within the context of improving product sustainable performance (Bovea & Pérez-Belis 2012); Faulkner & Fazleena (Faulkner & Badurdeen 2014), Lu ((Lu et al. 2012) Feng et al. (S. C. Feng et al. 2010) developed a series of techniques and methodologies evaluating the sustainable performance of production. As an important initiative to assess materials' environmental performance, the LCA should integrate with other emerging sustainable production support tools, e.g. regulations and directives, into the standard product development process, in order to reduce emissions and enhance product sustainability performance at the design and production level.

The current LCA software and applications overwhelmingly rely on the desktop operating environments, and even the most powerful LCA software packages are designed to offer services for single user based application scenario, which restricts the LCA's scalability as a tool in evaluation environmental performance at the level of supply chain or value chain. With the increasing pressure from the regulating authorities and consumers, companies require a more advanced tool supporting the powerful and flexible environmental impact evaluation, as a result, companies are facilitated in the lowering of their environmental impacts and increasing of their competitiveness with respect to other suppliers, manufacturers and any other involved stakeholders. This demands the LCA related services to be delivered with more flexibility and dynamism in a solution platform by transforming complex business processes and complicated IT services.

1.2. Aim and objectives

The main aim of this research is to offer a novel ICT based solution to assess product environmental performance and support sustainable production activities. The solution will be conceptualized by a framework that employs the LCA and value chain mechanism, additionally, a LCA service platform will be developed to implement the proposed solution that includes the integration of multiple powerful software/applications. Companies can use this platform to evaluate their resource inputs and outputs as well as emissions, and calculate the impacts of their products. By gathering required data along specific value chain, from raw materials through to the point of sale, reliable and comparable product-specific data is created in a cost-efficient way, supporting better, more environmentally oriented decision-making in sustainable design and production processes. Moreover, this research aims to develop a LCA based product development methodology, and it applies the major stages of product development process with providing the advanced tools and techniques, which include LCA methodologies, LCI database, LCA software, the EU regulations and directives, and standards for environmental management system. The novel methodology offers a new framework to enhance products sustainability at the design and production level.

In order to achieve the research aim, the following objectives have been created:

- To investigate the application scope, requirements and attributes of emerging tools and techniques that support the product development processes.

- To develop an integrated approach to assess products' environmental impacts and to support sustainable production.
- To develop the applications for end users, and clarify the application scenarios and services.
- To develop the SQL based database to support the developed systems and applications.
- To develop a web based product environmental performance assessment system including web and mobile client applications.

1.3. Structure of the thesis

Chapter 2 presents the findings of literature review, and is generally divided into three domains. The section 2.1 & 2.2 examine the attributes of a wide range of LCA methodologies, and new initiative for reducing emissions and improving resource efficiency, Product Environmental Footprint. Then, studies related to employing LCA framework in terms of sustainable production actives and multiple-objective evaluation (see section 2.3 & 2.4) are examined, in order to clarify the practical and theoretical drawbacks of LCA. Last, recent studies related to LCA based software and systems that implement environmental or environmental based multi-objective evaluations are reviewed (see section 2.3), which was conducted with the aim of clarifying the practical challenges of the existing LCA based tools, and the adopted software engineering technologies with these relevant systems and software, in order to develop a solution addressing the identified challenges.

Chapter 3 introduces the designed methodology and processes for undertaking this research, and the expected results of each research phrase are also presented with the aim of ensuring the aims and objectives of this study are met. A variety of software engineering tools, and the system development environment, communication protocol is introduced in this chapter. Additionally, the quality of the adopted data source for case studies are assessed, so possible limitations for the analysis results are clarified.

Chapter 4 describes a solution assessing product environmental performance at the level of value chain, and the solution is demonstrated by a conceptual framework and explained with descriptions for the application scenarios. Furthermore, a novel LCA service platform is proposed, which is consisted of three implemented system/applications offering required services for the proposed solution. The interfaces for clients, mechanism for the data conversion within the platform, workflows and methods for creating LCI management services, and the core high-performance libraries implementing the calculation service are briefly reported.

Chapter 5 examines a variety of sustainable production support tools, including LCA software tools and databases, standards of environmental management system, and the EU regulations and directives related to sustainable development. The scope, attributes, and requirements of these tools and techniques are examined with the aim of developing a set of specifications for the toolbox. The findings are used to develop a sustainable production support toolbox, which is a web portal from the technique view developing with JavaScript and HTML relevant web technologies.

Chapter 6 examines the data formats of LCI database, and the components and differences of these data formats. Novel methods for converting EcoSpold1 to SQL format are developed and demonstrated by presenting the data extraction programming scripts and applying in a SQL database management client. Last, a framework demonstrating the management for LCI data and LCA based methodology are presented, which is implemented a Java based GUI application.

Chapter 7 describes the development for a web based product environmental performance evaluation system, which includes the explanations of the calculation rationale, service development for invoking a third-party high-performance calculation library, and converting a desktop software into a web based LCA tool. Moreover, a novel iOS client application is developed that enables to implement remote LCA services, which is a LCA service based mobile application. Last, the development of the database for the LCA service platform are reported, the main entities of the database include Product entity, Process model entity, Calculation entity, Indicators entity, ecoInvoice entity, Classification of inputs entity, and Overheads entity. Three services implementing the massive data communication and integration within the system are developed, which are Data Service, Data Integrator Service, and Registry service. The developed system delivers efficient web based LCA calculations, and it performs flexible and collaborative environmental performance assessment, which is also one of the core novelties of this study.

Chapter 8 presents a study describing a LCA for the shampoo product. The product is manufactured by a UK based company, and the main adopted product LCI data are provided and suggested by the company. The life cycle stages of the shampoo product, and main activities within these stages are modelled, and the boundaries and functional units for the analysis targets are introduced. Then the LCA analysis results are examined under three scenarios respectively: cradle-to-gate, cradle-to-distribution, and cradle-to-grave.

Chapter 9 presents a study describing a successful Sustainable Flooring Product development process, by using the tools and techniques included in the Sustainable Production Support Toolbox. A framework demonstrating the integration of these state-of-art tools and techniques into general product development process are produced, with explanations of the application requirements and scope. The main material of the designed floor panel is Sheet Moulding Compound (SMC), and the designed prototype are evolved from Product Design Specification, Concept Design, Detailed Design, and Prototyping and Testing. The analytical results of LCA are not only able to assess the design and materials environmental performance, but also are used as benchmarking values for design iterations.

Chapter 10 concludes the findings obtained in this research by offering a summary, highlighting the study novelties, and contributions in theoretical and practical level. The suggestions and methods for future study are also discussed.

Chapter 2: Literature Review

2.1. LCA based methodologies

Life cycle assessment (LCA), as defined by the ISO standard, is a multi-criteria and systematic procedure for compiling material and energy flows of a product or service and evaluating the environmental impacts potentially generated throughout its life cycle (ISO 2006a). The basic rationale behind the LCA is about tracking the major stages and processes of the product lifecycle, from raw material extraction, manufacturing, product use, and recycling through to final disposal, in order to identify and quantify the environmental impacts that occur at each stage. LCA has been recognised as a key tool for identifying the potential environmental impacts of products and services.

According to ISO 14040 (ISO 2006a) and ISO 14044 (ISO 2006b) standards, LCA is carried out in four steps: goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and finally the results interpretation. The first step is to define the analysis scope of environmental impact. The LCI involves collecting and building the inventory data for the analysis of products or services. In LCIA, the boundaries and data are applied to the product or service system under investigation, which usually involves a series of mathematical calculations. The interpretation is the final step during which a summary of the calculation results is given in accordance with the goal and scope definitions. In this step, the weighting and grouping can provide a further degree of inconsistency among LCIA results (Ahlroth et al. 2010). The grouping method refers to classify the environmental impact categories based on the study objectives, or their relative importance. The weighting refers to scale the environmental impacts according to a group of indexes representing their relative importance, and these indexes are determined by the selected LCA methodology.

The LCA methodology is required to apply in the LCIA phrase, by which the aggregation of the inventory data showing emissions and resources consumptions are converted into impact categories. The impact categories are also known as indicators, and these indicators link different types of LCI results and cover different impact categories and characterization models. Common impact categories are climate change, human and ecotoxicity, acidification, eutrophication and resource depletion. The indicators of the specific impact categories can be classified to midpoint or endpoint. A midpoint impact for the impact category climate change is for example kg CO2-equivalents/kg gas, a referring endpoint impact could be impact on nature (such as a rise in sea level or global average temperature). While endpoint indicators allow users to clarify concrete environmental impacts, their calculation is associated with higher uncertainties than midpoint indicators. The main LCA methodologies are reviewed, and their features and midpoint/endpoint impact categories are presented in Table 2.1.

In addition to ISO 14040/44 there are other specific assessment frameworks for environmental assessment on product level such as ISO 14067: Carbon Footprint of Product (Garcia & Freire 2014), French Environmental Footprint (BPX 30-323) (PRé 2012) and UK's Product Carbon footprint guidelines PAS 2050 (BSI 2011). They all employ the Life Cycle approach as a basis from ISO 14044 standard.

The carbon footprint defined in ISO 14067 of product international standard specifies principles and requirements for studies to quantify the carbon footprint of a product, based on the LCA specified in ISO 14040/44. However, it only allows users to assess the impact category of climate change.

The French Environmental Footprint (BPX 30-323) establishes the prospect of regulatory communication of environmental information relating to the product. It is based on the standards ISO 14040/44 and follows international European normative developments (PRé 2012). BPX 30-323 gives general principles for the environmental communication of products. The environmental communication includes indicators limited in number and specific to a category of product.

UK's Product Carbon footprint (PAS 2050) specifies the assessment of the life cycle greenhouse gas emissions of goods and services. The PAS 2050:2011 specifies requirements for the assessment of the life-cycle GHG emissions associated with the life cycle of goods and services ("products"), also based on life cycle assessment techniques and principles provided in ISO14040/44 (European Commission 2011a).

After extensive comparison, the methodologies can be categorised into two groups: resource based and emission based. The resource based methods focus on resources (inputs) taken from the nature with resource indicators (e.g. Cumulated Energy Demand); emission based methods focus on outputs to the nature, assessing one or multiple emissions (outputs) with the help of extended assessment models (e.g. CML 2002, ReCiPe).

As the European Commission specified in its publication "Impact Assessment Guidelines", the selection of methodologies should fulfil the so-called RACER criteria (European Commission 2006). RACER is an evaluation framework used to assess the value of scientific tools and it has the following criteria (Lutter & Giljum 2008):

- Relevant: closely linked to the objectives to be reached.
- Accepted: acceptance by policy makers and industry.
- Credible: credibility regarding methodological transparency.
- Easy: ease of monitoring.
- Robust: robustness in terms of data quality.

It is necessary to notice that IMPACT World + and LC-Impact are relatively new methodologies. At the time of writing this thesis, the normalisation factors of IMPACT World + and midpoint characterization factors of LC-Impact have still not been completed according to the information of their official websites (IMPACT World 2016; LC-IMPACT 2016). Moreover, four core points related to the LCA methodology are concluded according to the review findings, with the aim of clarifying the pathways to select the suitable method:

- the official statement expressing the essential characteristics and function of a method.
- the supportive data properties and their availability.
- the unit of the environmental impact measurement
- the inner structure of environmental impact indicator compositions as this determines the difficulty level of analytic results interpretation.

Table 2.1. Brief descriptions and environmental impact categories of major LCA methods

Methods	***Descriptions***	***Midpoint Impact Categories***		***Endpoint Impact Categories***
Ecological Footprint	It considers biologically productive land and sea area to produce all consumed products and absorb generated waste (Hischier et al. 2010)	land occupation climate change nuclear energy use		global hectar (Consumption of hectare with global average bioproductivity, gha)
Cumulated Energy Demand	It assesses primary energy required for production, use and disposal of a product (Hischier et al. 2010).	fossil nuclear primary forest biomass	geothermal solar wind water	non-renewable resources, renewable resources
CML	It assesses specific impact categories and this method is divided into two versions: baseline and non-baseline. It only assesses midpoints' impacts (Guinée 2002).	depletion abiotic resources climate change stratospheric ozone depletion human toxicity marine ecotoxicity	fresh-water aquatic eco-toxicity terrestrial ecotoxicity photo-oxidant formation acidification eutrophication	N/A
Eco-indicator 99	It replaces Eco-indicator 95, and covers all emission categories and parts of the resource categories (PRé 2015).	climate change ozone layer depletion acidification/eutrophication carcinogenic fossil resources	Ionizing radiation ecotoxicity land use mineral resources respiratory organic respiratory inorganic	human health, ecosystem quality resource depletion

IMPACT 2002+	It is mainly based on Eco-indicator 99 & CML 2002 linking 14 midpoint categories to four damage categories (Weisbrod & Van Hoof 2011).	human toxicity respiratory effects Ionizing radiation ozone depletion photochemical oxidant aquatic ecotoxicity terrestrial ecotoxicity	aquatic acidification aquatic eutrophication terrestrial acid/nutr land occupation global warming non-renewable energy mineral extraction	human health ecosystem quality climate change natural resources
USEtox 2.01	It is a scientific consensus model for assessing human and ecotoxicological impacts of chemical emissions in life cycle assessment (Fantke et al. 2015).	freshwater ecotoxicity	carcinogenic non-carcinogenic	ecosystem quality human toxicity
EDIP 2003	It is a follow-up of the EDIP 97 methodology, and it covers only emission categories and considers midpoint impacts (Ciroth 2014).	global warming ozone depletion acidification terrestrial eutrophication aquatic eutrophication (N-eq, P-eq) Ozone formation (human, vegetation)	human toxicity (exposure route via air, water, soil) ecotoxicity (water acute, water chronic, soil chronic) waste (hazardous, slags/ashes, bulk waste, radioactive waste)	N/A
IMPACT World+	It is developed as a joint major update to IMPACT 2002+, EDIP, and LUCAS methodology, and it assesses local and regional impact categories (Bulle et al. 2014).	human toxicity photochemical ozone formation ozone layer depletion global warming	ecotoxicity acidification eutrophication water land use resource use	human health ecosystem quality resources and ecosystem services

ReCiPe	It is a follow up of Eco-indicator 99 and CML 2002 methods that integrates and harmonizes midpoints and endpoint approaches (Goedkoop et al. 2009).	climate change ozone depletion terrestrial acidification freshwater eutrophication marine eutrophication human toxicity photochemical oxidant formation particulate matter formation terrestrial ecotoxicity	freshwater ecotoxicity marine ecotoxicity ionising radiation agricultural land occupation urban land occupation natural land transformation depletion of fossil fuel resources depletion of mineral depletion of freshwater resources	human health ecosystem quality resources
ILCD 2011 Midpoint+	It analyses the emissions into air, water and soil, as well as the resources consumed in terms of their contributions to different impacts on human health, natural environment, and natural resources (European Commission 2011c).	climate change ozone depletion human toxicity particulate matter/respiratory inorganics photochemical ozone formation	ionizing radiation impacts acidification eutrophication ecotoxicity land use and resource depletion	N/A
TRACI 2.1	It is a tool for the reduction and assessment of chemical and other environmental impacts (Bare 2011). It is a midpoint oriented LCA method (Hischier et al. 2010).	acidification ecotoxicity eutrophication ozone depletion smog depletion climate change	resource depletion (fossil fuels) human health (air pollutants criteria, carcinogenic, non-carcinogenic)	N/A

LC-Impact	It is an environmental assessment method focused on a global level, and spatially differentiated characterization factors are developed to support the assessment on a regionalized scope (Ponsioen et al. 2014).	water stress climate change toxicity photochemical ozone formation particular matter formation lionising radiation	ozone depletion eutrophication land stress acidification fossil resource scarcity mineral resource scarcity	human health ecosystem quality resources
Ecological Scarcity 2013	It weights environmental impacts with eco-factors, which are derived from political targets or environmental laws (Frischknecht & Knöpfel 2014)	water sources energy sources mineral sources land use global warming ozone layer depletion main air pollutants and PM carcinogenic substances into air heavy metals into air water pollutants POP into water	heavy metals into water pesticides into soil heavy metals into soil radioactive substances into air radioactive substances into water noise non-radioactive waste to deposit radioactive waste to deposit deposit waste	environmental loading points

2.2. Product Environmental Footprint (PEF)

To further classify the indicators environmental categories have been derived from current standardization activities of the European Commission. In its Roadmap to a Resource Efficient Europe, the European Commission developed a dashboard of indicators to illustrate complex resource use impacts. This dashboard contains the categories material use, land, water and carbon (European Commission 2012b). Also, within the Product Environmental Footprint (PEF) a more comprehensive range of categories is provided (Manfredi et al. 2012). These categories of the PEF and the EU dashboard are illustrated in Table 2.2.

Table 2.2. Environmental impact categories for EU dashboard and PEF

EU Dashboard	Product Environmental Footprint
Abiotic resources Biotic resources Land use Water	Abiotic resources, Aquatic eutrophication, Acidification, Land use, Respiratory inorganics, Human health, Water, Terrestrial eutrophication, Ozone depletion, Climate change, Ionizing radiation, Ecotoxicity, Ozone formation

The Directorate-General for the Environment of the European Commission and the Joint Research Centre (JRC IES) have worked together to develop the methodology of the 'Environmental Footprint'. The methodology refers to a way to measure the environmental performance of products (PEF) (Manfredi et al. 2012) and of organisations (OEF) (Pelletier et al. 2012) by adopting a life cycle approach and basing on the material, energy, emission and waste flows occurring throughout the supply chains. The two slightly different variations were developed within an EC-Project delivering its first results in March 2011 and the final methodological guide in April 2013. Various standards and guiding documents served as references for an attempt to develop a harmonised European methodology, which include

International Reference Life Cycle Data System (ILCD) Handbook, ISO 14040/44, WRI/WBCSD GHG protocol, ISO 14025, PAS 2050, BP X30, Sustainability Consortium, Global Reporting Initiative, WRI GHG Protocol, CDP Water Footprint, ISO 140064, DEFRA guidance on GHG reporting, etc. A pilot phase for both PEF and OEP and a final technical guide is expected within the next years (2016 end of pilot phase) (European Commission 2016).

The Environmental Footprint aims to specify the ISO 14040/44. In the final draft of the Environmental Footprint Guide (Product Environmental Footprint (PEF) Guide) the procedure to solve allocations is similar to that of ISO 14040/44. However, as outcome of the ongoing pilot phase standardised allocation factors for specific product category are expected.

2.3. Sustainable value chain studies

The LCA is widely used by many studies related to enhancing the green performance at the level of product value chain. Lake used LCA to examine the carbon emissions and applied the analytical results into the decision-making support system that is used to assess the overall sustainable performance in the UK construction industry (Lake et al. 2015). Dadhich et al. developed a hybrid methodology measuring plasterboard value chain, and LCA was used to identify the hotspots of the greenhouse gas emissions through the plasterboard life cycle (Dadhich et al. 2015); Tsai et al. developed a mathematical model supporting decision-making towards activity-based costing (ABC) system for Taiwan electrical and electronic industry, and the LCA methodology schemas were programmed into the ABC system evaluating the green production decisions (Tsai 2015). Croes & Vermeulen introduced a “bottom-up” and “product specific LCA” to measure the environmental and social costs of products, and a “Eco Social Cost Unit” (ESCU) indicator was developed to allocate and transfer the costs through the value chain. In this study, the ecoCost method was adopted to determine the price factors that are applied to analysis the relative impact categories associated with the sustainability issues (Croes & Vermeulen 2015). Neto et al. implemented a LCA with CML method for the supply chain of a wine product. The product company offered specific LCI for viticulture stage, and the missing data was fulfilled by the ecoinvent database. The study results show that the major environmental impacts are contributed by the viticulture stage (more than 50%) and bottle production process. Moreover, the analysis identified that 78% of the Global Warming impact is caused by the domestic distribution (Neto et al. 2013). Čuček et al. developed the concept called eco-profit that is an evaluation index representing the difference between eco-cost and eco-benefits within the LCA framework, and the eco-profit was used to examine the biogas production process through performing the sustainable mixed-integer liner programming (MILP) synthesis. The evaluation results were interpreted for creating optimal solutions for biogas product value chain (Čuček et al. 2012).

These studies acknowledge the importance of LCA in offering quantitative evidences to assess and improve sustainable performance of the supply chain. However, the data used in these studies are statistic-based from the companies, relevant industry associates, or commercial databases, which usually reflects the out-of-date situation in a given time and fails to continuously describe the real situations. Therefore, dynamically updated data are required to offer more accurate and efficient evidences for assessing the environmental performance within the context of supply chain sustainability improvement.

2.4. Sustainable production studies

This section will introduce the recent studies linking the LCA and sustainable production activities including the design, manufacturing, recycling. etc. Keller et al. introduced an integrated life cycle sustainability assessment (ILCSA) methodology that combines the outcomes of the LCA, life cycle costing, and social life cycle assessment. This study used the ILCSA to examine the biorefineries production scenarios, and demonstrated an ex-ante decision support for the sustainability assessment (Keller et al. 2015). Lanfang et al. developed a LCA based modelling approach, and Material Energy Flow Analysis (MEFA) was integrated to identify the recoverable and unrecoverable resources in the more complex product systems. The study examined the methodology with tracking the lifecycle iron and energy use of producing construction steels (Lanfang et al. 2015). Ribeiro et al. integrated the LCA, product design and supply chain framework to build an approach evaluating the emerging sustainable manufacturing technologies, and this approach performs environmental and economical level evaluation with the life cycle engineering foundation. The study demonstrates the feasibility with evaluating innovative manufacturing technologies (e.g. three-dimensional contoured thermoplastic sandwich structures) in the bicycle rocker design process (Ribeiro et al. 2015). Shin et al. used LCA to acquire quantitative results and integrate them into the process planning algorithm for assessing green performance of machine operations, and a Green Productivity Index was developed to represent overall environmental and productivity performance for the manufacturing phase (Shin et al. 2015). Bernier et al. developed an optimal methodology that minimizes costs to achieve zero life cycle impacts through integrating the LCA into a single or multi-objective process design optimization scenarios. The study used Ecocosts 2007 impact assessment method to evaluate compensation costs for reducing carbon dioxide emissions of a natural gas combined cycle power plant (Bernier et al. 2013). Scheepens et al. used the EVR and Circular Transition Framework to develop a new approach guiding the design of sustainable business models, and the eco-costs was applied to analyse the environmental impacts of business activities on a system level. The feasibility and utility of the approach was demonstrated by a case study describing the recreation of a sustainable water tourist system in Netherlands (Scheepens et al. 2015). Romli et al. developed an integrated eco-design-making (IEDM) methodology, and the LCA results were incorporated in the Eco-Process model and conceptual Eco-QFD (quality function deployment) framework, in order to offer quantitative and quality evidences to support sustainable product design (Romli et al. 2014). Mestre & Vogtlander developed a design intervention method to increase the customer perceived value, which used the eco-cost to examine the eco-burden and relative values among multiple design solutions for cork products (Mestre & Vogtlander 2013). Casamayor & Su used the eco-indicator 99 that is a LCA methodology to examine the environmental performance of the main components of lighting products and their production processes. The analytical results were used in benchmarking for each optimal design iterations (Casamayor & Su 2013). Morales-Mora et al. examined the carbon emissions and wastewater flow of manufacturing acrylonitrile products in Mexico, and the LCA results were used to support that the new design of the production process has a major emission reduction than the old design (Morales-Mora et al. 2012).

The reviewed studies prove that as a technological progression, the LCA enables to lead main production activities into a sustainability level. This inspired the core idea of this research that the actors in the same supply chain can contribute in building LCA or LCA based evaluations in terms of providing required data and designing evaluation indicators, and the evaluation results are shared and distilled into actions reducing the environmental burden.

2.5. ICT studies related to LCA system and software

Developing new tools implementing custom LCA based calculations in a professional scenario, or integrating those new tools into existing enterprise level systems (e.g. ERP, PDM) are new research directions. Zhang et al. proposed a LCA-oriented and ontology-based semantic representation model and methodology to model product life cycle. A system prototype was also developed by using Web service related technologies, by which the elementary flows and process flows can be queried, and presented in the form of Resource Description Framework (RDF) graph in an Ontology application. The study outcomes demonstrate a new solution for representing LCI, which enable practitioners to easy classify, share and formalize product life cycle (Zhang et al. 2015). Clavreul et al. developed an environmental assessment system to implement LCA towards complex product systems. The key novelties of this system include modelling heterogeneous materials flows that is not supported by the existing LCA software; using a toolbox to enable easy set-up scenarios modelling; offers tools for users to implement uncertainty analysis by performing Monte Carlo simulations (Clavreul et al. 2014). Kalakul et al. developed a new LCA software, LCSoft. Except the general LCA software functions (i.e. calculation; LCI management), this software also performs estimations of environmental impact characterization factors by using group contribution^{+} method (GC)$^{+}$ for assessing chemicals environmental performance, and provides interfaces for integrating with other design tools. The environmental impact of a bioethanol production process is calculated by LCSoft, the results of which is compared with SimaPro calculation results, aiming to examine the software performance (Kalakul et al. 2014). Ciroth et al. proposed a solution integrating LCA software into Product Data Management (PDM), in order to obtain high-quality product data and support the workflow of Design for Environment (DfE). The solution is implemented by a connector application (eLCA) which is an interface linking LCA software and ENOVIA platform (i.e. a PDM system) by Java API or web services, and this connector performs the general LCA software functions (Ciroth et al. 2013).

2.6. Summary of the review

The reviewed studies show that existing LCA based practices can provide up-to-date information only for a short time after they have been conducted, and the scope is often limited to individual companies, processes or products. On the other hand, modern society thrives on a diverse and complex economic structure, which makes the acquisition of reliable data even more important and difficult. Furthermore, high-quality data is a prerequisite for offering solid information to any kind of decision-makers, therefore a consistent method of data gathering for assessing the resource use of products and services is necessary (Geibler et al. 2013).

The reviewed studies also prove that LCA related indicators are suitable for incorporation with diversified economic and social evaluation indicators, in order to pursuit the multi-objective evaluations within the context of sustainable performance improvement. However, these studies also indicate that it is still a barrier for non-LCA experts to conduct LCA, which requires a tool offering powerful and flexible services including: defining the evaluation indicators and its components; defining and modifying the calculation schema; gathering dynamic LCA related data.

Therefore, an integrated approach offering the advanced LCA based functions are required to provide the flexible and powerful evaluations, the dynamic data regarding the product raw materials, main components, production processes, transportation, consumption, and even end of life. Particularly the data depicting the product consumption stage will strongly improve the calculation accuracy and further to improve the performance of the solution. The following chapter will describe the methodology to conduct this research project.

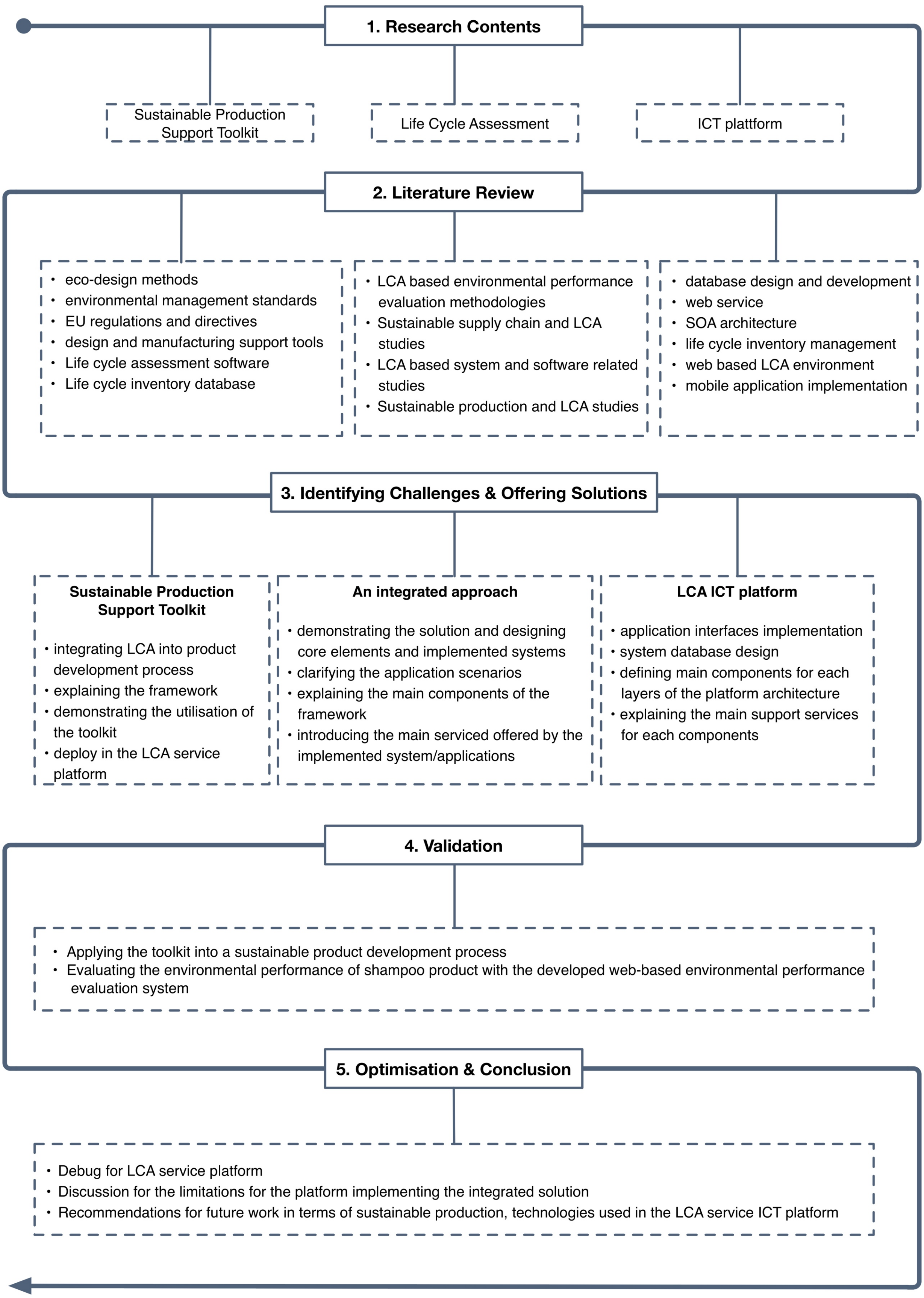
Chapter 3: Methodology

3.1. Research design and outcomes

In order to achieve the objectives and aims of this research project, a comprehensive methodology has been designed, which is introduced in the following sections. Five steps consist of the designed methodology in this research. The general rationale among these steps and their outcomes for each sub-task are shown in Figure 3.1.

Research contents: The initial aim of this research was to investigate the emerging tools for sustainable production, and the LCA technologies were identified as the initiative to improve products' sustainability performance, and facilitate companies' environmental related activities. The research towards sustainable production is divided into a wide range of topics: eco-design, production process refinement, green supply chain improvement, sustainable policy creation, etc. In order to clarify the role of LCA in these relevant studies, and identify the limitations of LCA in theoretical and practical level, recent studies are required to review and criticise.

Figure 3.1. Main steps and their outcomes for the research methodology



<u>Literature review</u>: Extensive literature review is conducted in this phrase, which are broadly categorized into three domains: main LCA environmental performance assessment methodologies; studies related to employing LCA in supply chain sustainability improvement, and sustainable productions; ICT technologies used in the LCA related system and application. It clarifies the role of LCA in these studies, and identifies the theoretical and practical limitations for LCA implementations. Moreover, it lays out the core idea for developing the integrated solution in this research, and clarify the practical and theoretical challenges related to the relevant research fields.

<u>Identifying challenges and offering solutions</u>: The challenges and limitations related to sustainable production and the LCA are obtained through reviewing the relevant studies, which are thoroughly discussed in Chapter 2. Three solutions are proposed with the aim of addressing these identified issues and challenges, which include:

- integrating the LCA technologies into the sustainable product development process.
- constructing an integrated solution implementing environmental impact accounting through life cycle and value chain of products.
- developing a series of end user applications and a supporting system implementing the functions and services described in the proposed solution.

The proposed solution involves developing a LCA service system, therefore, the following. tasks are required to consider and achieve:

- Building the database entity table that reflects the general attributes of LCI.
- Communication technologies that offer high efficient performance in massive data transmission.
- Techniques used to develop client applications including web and mobile applications that enable to run in different platforms.
- Methods and technologies for constructing the system architecture.

<u>Means of validation</u>: Two studies are separately conducted in order to respectively validate the outcomes of this research. The LCA based product development methodology and sustainable production support toolbox are applied in the study of a sustainable flooring product development process, and the prototype of the designed flooring product successfully met the requirements of the relevant standards and regulations in the EU. The performance of the web based product assessment system is validated with a LCA for the shampoo product. The calculation results acquired in the validation process are also used to compare with the calculation results provided by the commercial LCA software, in order to assure that the same conclusions are supported by these calculation results from two different evaluation tools.

<u>Optimization and conclusions</u>: The bugs detected in the validation process will be fixed to verify the functionalities of the developed applications. The research contributions and limitations will be discussed in the theoretical and practical level. Future research questions and suggestions will be offered as well.

3.2. System development technologies and environment

The LCA service platform has been designed in compliance with the requirements of Service Oriented Architecture (SOA) framework, as SOA is an important concept for developing and integrating services across massive computer systems over Internet, and the services are usually required for meeting business demands. SOA performs easy and flexible assembly and integration of these services into the particular applications. From the technique perspective, the rationale of system is to employ Web based communication technologies to deliver LCA related services through client applications in web and mobile environments. Therefore, the main technologies used to develop the system and application are introduced in this section.

<u>Web services</u>: A Web Service is a method enabling communications among devices over the Internet. The common definition for a Web service is 'software system designed to support interoperable machine-to-machine interactions over a network' (W3C 2004). A Web service's interface is usually composited by mark-up language, and a client calls a Web service's functionality by using this interface. These descriptive explanations are usually placed in a Universal Description Discovery and Integration (UDDI) repository in order to monitor and receive a Web service on the Internet. Within Web services development, SOAP (W3C 2007) and REST (Fielding 2000) are the most widely used communication protocols.

<u>Simple object access protocol (SOAP)</u>: XML is used by SOAP to specify the organizational structured exchange information. SOAP services are constructed by machine readable languages implementing service activities, which can be programmed by adopting the Web Service Description Language (WSDL) (W3C 2001). WSDL is not compulsory for SOAP development, but it is convenient to achieve automated generation of application client and server codes. There are a wide range of transportation methods supporting SOAP, e.g. HTTP, TCP, and UDP. HTTP is the standardised protocol for Web service, because it is of the ability to going through firewalls, and facilitate the security and identification issues. The main issue related to SOAP is that it overwhelmingly relies on XML that is of verbose nature.

<u>Mark-up language</u>: Web Services are annotated by mark-up languages which also support the design and composition of the service. Service descriptions can be created from existing code through using automation tools. WSDL is a type of mark-up language used in SOAP for specifying a service that is characterized as a set of network endpoints. The endpoints interact with a binding, and they also define methods that are used to invoke a service, hence, a reusable message is described and performed by the relevant binding.

The architecture of the proposed ICT platform is designed with multiple layers that offer a number of services to ensure all the components to work in compliance with the requested functions. The IDE (Integrated Development Environment) used in this research is Eclipse, and the system repositories are developed in MySQL platform.

Compared with the server side, the development of client applications is straightforward from the technical view. The user interfaces for a standalone application or having been integrated into the development environment is not deeply discussed in this research, as which is not the key research objectives. The prototype of a consumer application interface is an example demonstrating the utility of a mobile application for the consumer side end user, which is developed in a standard iOS based application development environment: Xcode platform with Swift programming language.

3.3. Quality analysis for source data used in case studies

All the data used in this research is mainly about the inputs and outputs associated with the flooring product and shampoo product. The quality of these adopted data varies considerably depending on the sources, which influences the accuracy of the finalised calculation results. There are three type data sources adopted in this study, and their quality are rated as follows:

- Primary data, if provided by first hand source directly connected to the analysed case (e.g. the product manufacturer).
- Secondary data, if gathered from informed but not directly connected source to the analysed case (e.g. third-party database; relevant studies).
- Tertiary data, if taken from generic source that are assumed to be equivalent to the analysed case (e.g. governmental departments' report).

The data sources and their quality assessment rate involved with the two products are presented in Table 3.1 and Table 3.2. The data quality evaluation deserves particular attention and extra efforts, as it affects the accuracy of the calculation results.

Average data are used for the product life cycle inventory modelling. For example, the distance between the manufacturing factory to the retailer shop; average heating time in a manufacturing process. The specific data value is not possibly acquired within the context of this research; hence, the accuracy of the finalised analysis results would be moderated by adopting those average figures. Moreover, aggregating several data sources together for the LCI modelling and LCIA increases the uncertainties for the calculation results, because the methodology used by different databases varies in collecting and compiling their datasets.

Table 3.1. Data source and their quality level for the sustainable flooring product

	Primary	***Secondary***	***Tertiary***
Electricity and other energies in the manufacturing	The energy consumption of production stages (e.g. cutting, shaping) are obtained with estimation on operation machines.	ecoinvent 3.2 is the source for the UK production voltage delivered.	N/A
Waste management	N/A	N/A	UK Statics on Waste Report
Materials	Provided by the manufacturer	ecoinvent 3.2	N/A
Use	N/A	N/A	Referred the relevant studies
Transport	Suggested by the product manufacturer	ecoinvent 3.2 (vehicle emissions)	N/A

Table 3.2. Data source and their quality level for the shampoo product

	Primary	***Secondary***	***Tertiary***
Electricity and other energies in the manufacturing	The energy consumption time at each production stages are suggested by the manufacturer	Ecoinvent 3.2 is the source for the UK production voltage delivered	N/A
Waste management	N/A	ecoinvent 3.2	N/A
Materials	Provided by the manufacture	ecoinvent 3.2	N/A
Use	Suggested by the manufacturer	N/A	N/A
Transport	N/A	ecoinvent 3.2 (vehicle emissions) Average distance is suggested by the manufacturer in the UK	N/A

3.4. Summary

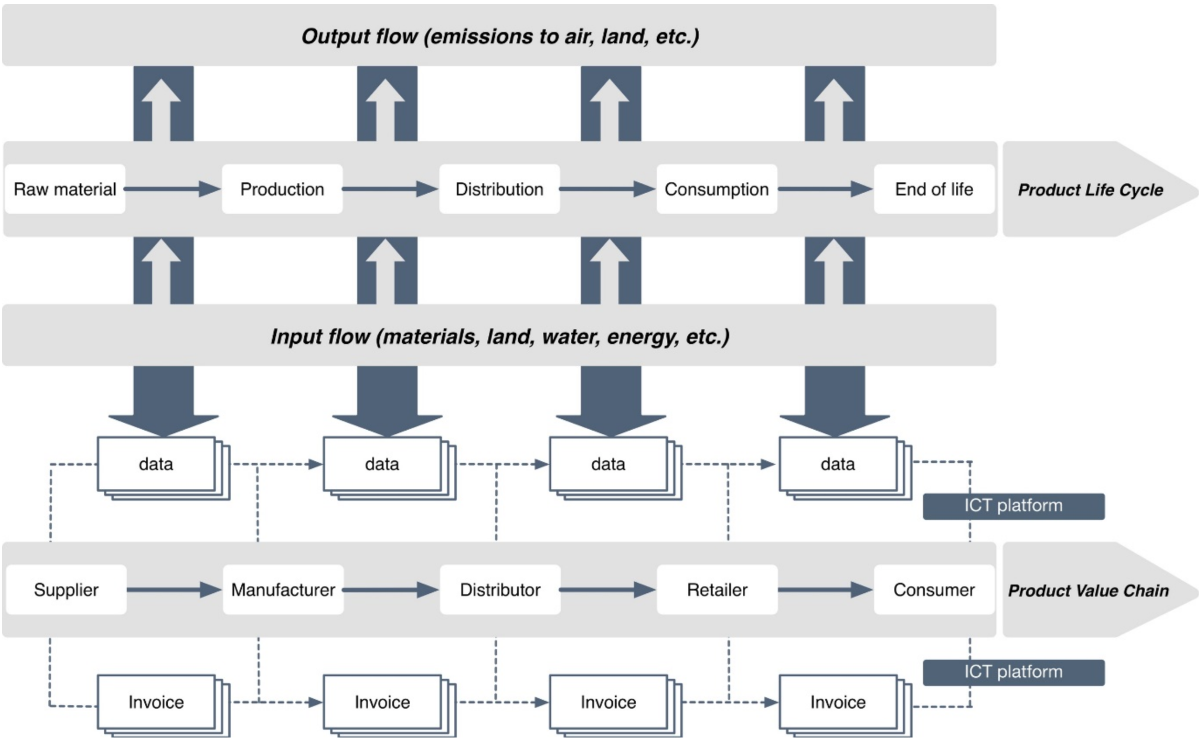
This chapter introduces the approaches undertaken for achieving the research objectives, which shows the general rationale of conducting this research. Main tools, techniques and development environments for the LCA service platform are introduced, which include Java programming language in Eclipse platform (server side), Swift programming language in Xcode platform (client side), Javascript in Eclipse (web front side), MySQL platform (repository side). The advantages of the adopted technologies are also discussed. The last but not least, the source data of the case studies are outlined, and their quality are assessed with three level. The possible limitations associated with the adopted data are also discussed, with the aim of clarifying the directions and targets for future refinement works.

Chapter 4: An integrated approach to assess product environmental performance and to support sustainable production

4.1. Data flow for sustainable production

This research aims to offer an integrated approach addressing the identified challenges with implemented systems and applications. The resource-accounting method collects relevant environmental data at each stage of a product life cycle, which represents the core function of the proposed approach. An extended approach is adopted in this approach and the main target of environmental accounting system are the environmental impacts occurred in the general stages of a product life cycle that includes raw material, production, distribution, consumption, end of life. The used resources and emissions in each stage are generally defined as input flow and output flow respectively, and both flows are quantized by diversified environmental performance datasets and other basic product data. These gathered data can be employed by the standard LCA methodologies (e.g. ReCiPe, carbon footprint), or other innovative multi-objective evaluation methodologies. Both type calculations are implemented through the pre-programmed calculation schemas. The data aggregated to support the calculation is recorded and input by the corresponding actors in the value chain into the centralized system through smart client applications within the proposed systems, and the data under accounting is transferred in the form of virtual electrical invoice. The electrical invoice is accumulated and distributed with the data transmit services among authorised end users. The breakdowns of evaluation results are interpreted by companies to improve product life environmental performance at the macro and micro level. The possible improvement activities can be conducted by employing the proposed sustainable production support toolbox. This proposed integrated approach is depicted by a framework, which is presented in Figure4.1.

Figure 4.1. The product life cycle data flow for sustainable production



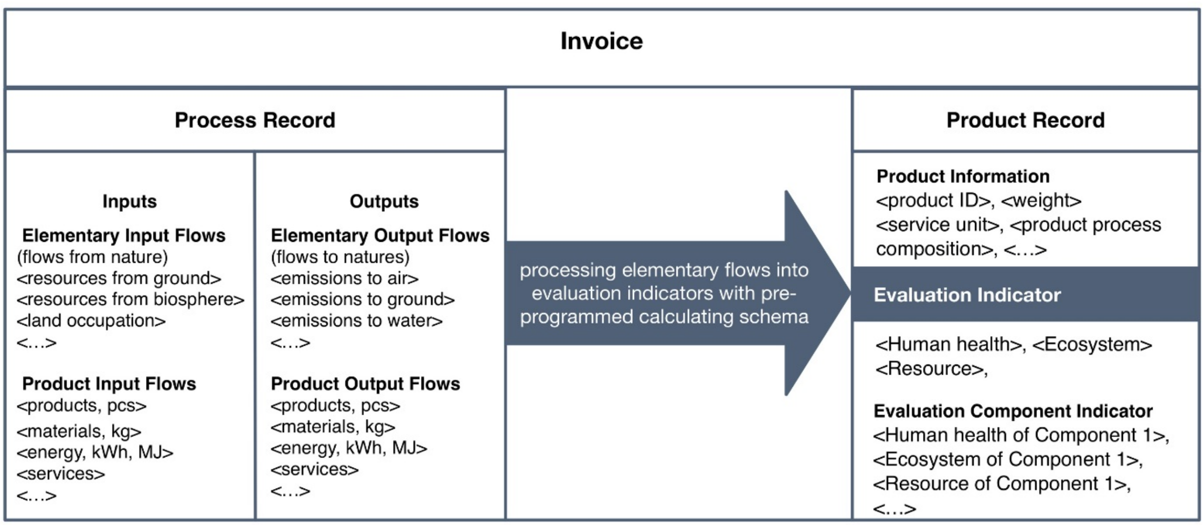
The invoice is the virtual form of the data communication among the main business partners in the product value chain. All the data recorded in the invoice are the key values used to evaluate and present product environmental performance, which is input by the business end users and is stored in the centralized system database. A general invoice shows the following data and information:

- a process and the quantity of the resulting product as input.
- the used resources and emissions to the nature for a process.

- the fetched data from the life cycle inventory database.
- the environmental performance indicators of the product at the given stage that is the fundamental data flow of the product record under accounting in this framework.

More specifically, the product invoice is usually consisted of the process record and product record. The process record includes the input and output flows that are mainly based on existing life cycle inventory of the company. They form the base for a derived environmental process indicator which allows a company to assess the resulting environmental impact or selected processes (or business units) within the company or for the product value chain. Except the common data (e.g. product ID, unit), the product record mainly shows the performance indicators aggregating all indicator values of processes related to the product flows received (considering specific allocation rules). The invoice is input and modified through the business HMI of the developed web and mobile based applications. A template of the general invoice components and its singular processing flow is presented in Figure4.2. The endpoint indicators of ReCiPe methodology are used in the diagram for the demonstration purpose.

Figure 4.2. A Invoice template and its processing flow



The environmental impact evaluation results are usually finalised by one or more indicator(s) value for either single product or a company's production over a certain period. The proposed web based product environmental performance assessment system offers flexibility in terms of the indicator selection, as it embeds the main LCA methodology options for choose.

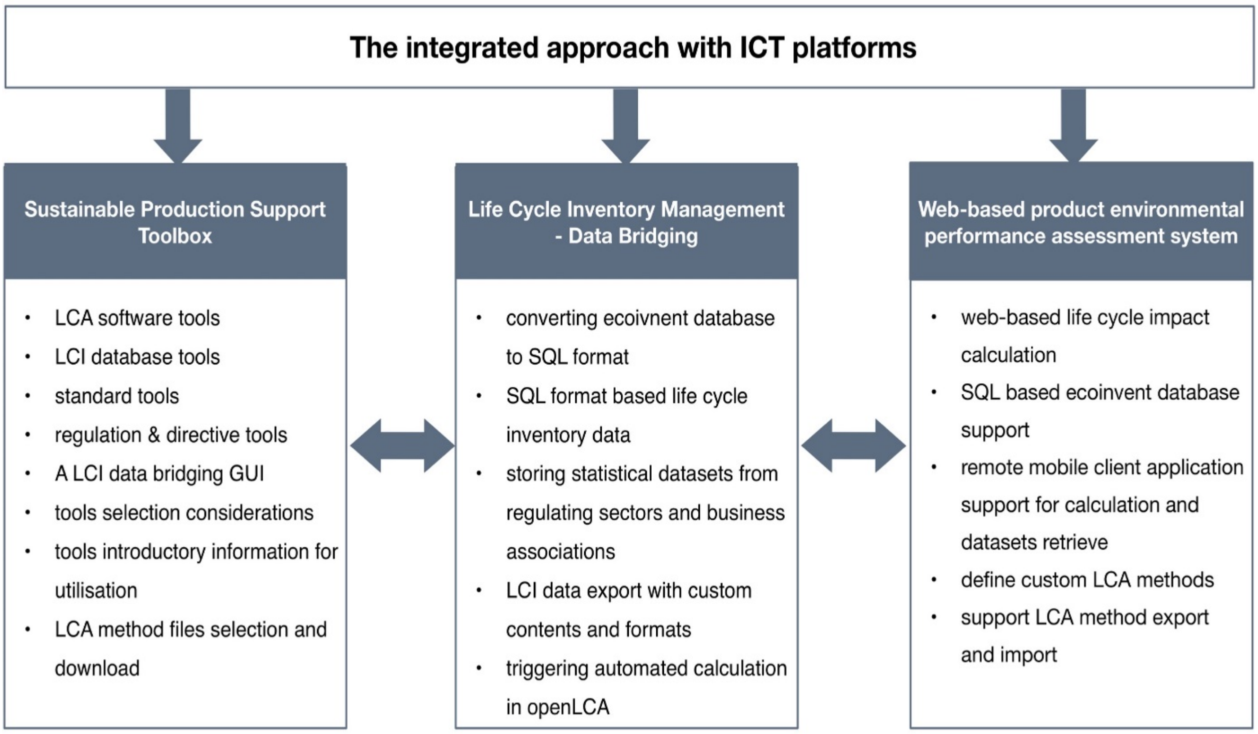
The ReCiPe method is adopted in this research to demonstrate the functions of the developed applications and its support system, and the values of its three endpoint indicators, Human Health, Ecosystem, and Resource, are the finalised performance indicators demonstrated by these applications and software. The values of eighteen midpoint indicators of the ReCiPe is also recorded in the system database, which is used for the interpretation of endpoint indicators, and analysis on roots that cause major environmental burden in the product life cycle. The endpoint indicators' values are recorded in the virtual invoice, and eventually are suggested to present in the product label in order to help consumers to select environmental-friendly products.

To avoid restricting the variety of indicators to be used, the proposed approach offers links with different environmental assessment methodologies and related indicators. In addition, the web based product environmental assessment system also demonstrates the ability to cope with any other chosen indicators in the future. For example, those suggested within the PEF initiative (e.g. eutrophication and acidification) could be added in the future work.

4.2. The integrated approach and the support systems

As the conceptualization framework shown, LCA service based platform is the key tool implementing the proposed solution, therefore, three novel main systems/application are proposed to achieve the required services and functions: sustainable production support toolbox, web based product environmental performance assessment system, life cycle inventory management system. Preliminary descriptions of these system and applications are discussed in the following sections, in order to demonstrate the overall rationale and feasibility of this proposed solutions for sustainable production. The relation between the solution and the supported system/application, and their roles are presented in Figure 4.3.

Figure 4.3. The integrated approach for the sustainable product development



4.2.1. Sustainable production support toolbox

The Sustainable Production Support Toolbox (SPST) is designed to help design and manufacturing engineers in businesses, particularly supply chain firms and small and medium- sized enterprises (SMEs), develop a more sustainable approach for growth. The rationale of this toolbox is to enable users to make the most of benefits of these state-of-art tools for achieving sustainable production by:

- Selecting the feasible tools and understanding the relevant methods and frameworks improving the ecodesign and sustainable production.
- Reviewing the requirements and scope of these included tools and techniques.
- Assessing environmental performance of the materials they acquire for production.
- Adopting the Environmental Management Scheme to motivate and drive continuous improvement in the company sustainable production activities.
- Interpreting the LCA results and distill them into design and production activities.

Moreover, the innovative strategy of using this toolbox is to rely on the analytical results of product environmental performance assessment, as these results are able to be applied as benchmarking values in the design and manufacturing phrases, and the methodologies for applying this toolbox in the product development process, will be demonstrated by the development of a sustainable flooring product.

4.2.2. Web based product environmental performance assessment system

This proposed web based assessment system essentially acts as a Calculator that implements the mathematical calculation of the product materials and processes' performance in diversified environmental impacts. This system is the core module of the proposed LCA service system and its main functions include: selecting LCA based calculation methods; modelling the life cycle of product or service; building life cycle inventory and defining product system boundaries; weighting the environmental impact results, and export the calculation results. Based on the findings of literature review, these functions are also provided in the professional LCA desktop software tools, but performing the same functions and services in a web platform with high efficiency is the major task for developing this system, which is also one of the core novelties of this study.

Furthermore, a mobile client application is also required according to the integrated approach requirements, in order to help consumers to retrieve the assessment results of their purchased products, and input the product end of life related data. More importantly, it is a powerful tool to increasingly collect the end of life (EOF) product data, as the lack of accurate EOF data is a major challenge for the existing life cycle inventory database and LCA practices, which is identified in the literature review phrases.

4.2.3. Life cycle inventory management – data bridging (LCIM-DB)

The main aim of developing a LCIM-DB is to address the challenge of LCI data processing and sharing in a web environment, which is also the barrier for improving the flexibility and performance of existing LCA software tools. Within the approach structure, a powerful LCI is particularly important as gathering LCI and product generic data takes time for companies adopting the system in the beginning time. Furthermore, with the support of the web technology, there is possibility to achieve continuous update for product life cycle related data, which means the life cycle impact assessment results would be more accurate, result in helping users to make accurate decisions in terms of environmental materials selection, design optimization, and manufacturing processes, etc.

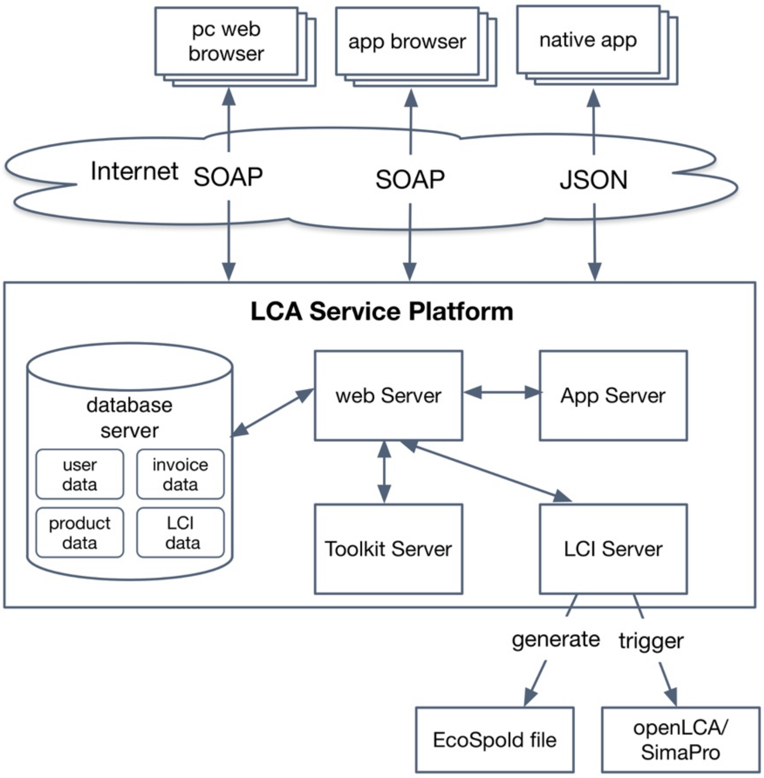
To implement this aim requires a standard data format for the fast and extensive processing and sharing services in the web environment. However, the existing LCI databases rely on XML format based datasets, which is not suitable for the web based product environmental performance assessment system requirements. Therefore, this research proposes to employ the powerful ecoinvent in the SQL based database for the web environment, which requires to develop methods for converting ecoinvent data format (i.e. EcoSpold) into SQL format. Furthermore, the user custom LCA methodologies and gathered LCI data in the system are required to export in order to apply in other LCA software, which involves multiple LCA method file formats conversion.

Apart from the process data related to the product LCIA, there are massive data related to product data (e.g. product ID, price), therefore an integrated database for the ICT platform is developed based on MySQL database manager to record and manage the product and process data of products that are accounted by the system. The database is installed in the server, which supports all the applications within the system to access the database and store the data into the database with security. When end users start get or post data in the system, the data are logged into the database in real time. The users are able to utilise the web and mobile client applications to access the recorded and stored data in the form of JSON format based web communication service. The validation process shows that the developed LCA service system can effectively work to online access the calculation results of accounted product, and other data reflecting product life cycle performance, and the applied remote communication methods enable end-users to remotely access the server to retrieve the calculation results and exporting the related datasets.

4.2.4. ICT architecture for the implemented systems

As Figure 4.4 shown, the main servers installed in the LCA service platform include web server, app server, toolbox server, LCI server and a centralized database. The communication between the applications including web and mobile clients to the platform are based on web services.

Figure 4.4. ICT architecture for the proposed LCA service platform



Web services are a distributed computing technology that allows the communication of applications based on different system and platforms. In this platform, Web services are used as Application Programming Interface (API) to transmit data over the Internet. Web services are also used for interaction between some application servers, such as web servers and database servers.

Web services for the platform are based on SOAP. Figure 4.3 shows the flow of how SOAP Web services work. When a web based client application invokes a method, for example, exposed as a service by platform, it creates and sends SOAP messages, which are based on XML grammar. For the native app client in the mobile phone, the data transmission format is JSON. HTTP is the primary protocol for Web services. A basic flow of the implementation of Web services is briefly reported as follows:

- A business client opens the application that is provided by the LCA service platform, which provides interfaces (e.g. GUI) to invoke a web service method (API) corresponding to some user use case.
- The application creates a SOAP request corresponding to the API and sends it to the server over the Internet using the HTTP protocol.
- The server receives the SOAP request and interprets it to the web service method invoked by the client.
- Then the server performs the operation and turns the result of the operation to the SOAP response.
- The SOAP response is sent over the Internet. The client retrieves the SOAP response and converts it to the result of operation.

The web servers within the platform use SOAP based services to interact with clients. Web servers are designed to deliver data among business servers. It consists of a SOAP web server and a dedicate API which communicates with app servers. When different Web servers work at the same machine, different service ports are allocated to the servers to differ from their functionality. That is, business servers and consumers can access the platform via the different ports.

Multiple software development tools will be used to develop Web servers. For example, Web server for consumers will be based on Apache web server and interact with Consumer HMI Application servers utilizing Web services. Different Consumer HMI application servers are located on a single computer or several computers.

As shown in the Figure 4.3, the Web server provides the dedicated API for the App server, Toolbox server and LCI server. That is, the three application servers are deployed in separate machines and connected each other using the API. The Web server is able to implement multiple sets of APIs.

The LCI related data managed by the LCI server which is one of software entities having heavy workload. When geographically distributed servers fetch LCI data and product data by invoking methods of the services at the same time, a large amount of data will be handled by the platform. Load balancing is a method that enables the load to be distributed across multiple machines, which is used to optimize the data flow to enhance the capacity of data delivery of the system. In this case, the load balancer is able to coordinate the distribution of load to optimize the data flow delivery services. For example, when web servers get product LCI data that are not provided by business partners, load balancing will be functioning to distribute the load properly, perform the querying of LCI database, and return results of the querying. With this method, multiple machines are able to handle the load in the coordination of load balancer. There are the following two load balancing modules:

- Web based service load balancing, which is performed by the Web server and Application server. Web server acts as a load manager while Application server is the real executor of load. When massive data exchange happens, the Web server distributes the load to Application servers with lowest usage. Each Application server works at an individual machine.

- Native app service load balancing, which is handled by the app server. The native app uses the same web service that are used to access other services.

The native app client accesses the services provided by the platform through the common web server in the communication with the Web server. The access from the web server to the app server is performed over a custom port specified by the administrator module installed in the web server. This hides the access to the app server from outside connections since the internal custom port can be blocked from external access. Within the LCA service platform, the database mainly stores the LCI data, product data, user information, invoice data. The database for platform is to be built with MySQL database management software. It will be placed in the database server which provides functions including data publish, search, locate in order to coordinate the resources, and to manage the data transmission of all resources in the system.

4.3. Summary

This chapter introduces a novel integrated approach to assess product environmental performance and support sustainable production. The approach is conceptualized by a framework. The offered functions and services for the implemented system are briefly reported, in order to demonstrate the feasibility and utility of the proposed solution for the sustainable production and the development improvement.

With the help of the user interfaces, companies define or select their environmental impact evaluation models by declaring all processes and overheads associated with each product, resulting in a product inventory, indicators and additional information (such as time and geographical reference). The product inventory represents the inputs and outputs between nature and industrial processes. They express a substance, or class of substances (e.g. bauxite, water or CO2) that has mass. Once defined to specific product or company, the ICT platform automates the evaluation of up-to-date environmental performance. The platform also contributes to a database of LCA inventories and statistics. Engineers and manufacturers can analysis the aggregated data with different levels of detail, and results can be interpreted and applied into the improvement of the raw materials selection, components design and production procedures, even environmental management system. To implement this described system and applications is a novel and challenging task, the adopted technologies and methods for the development phrases will be introduced in the following chapters.

Chapter 5: Development of a sustainable production support toolbox (SPST)

5.1. Introduction

Improving environmental performance is increasingly seen as necessary to improve economic performance and social responsibility, hence its measurement is a necessity to improve performance. This study proposes to develop an essential entry point for improving company sustainable development activities such as eco-design, production, sustainability reporting. As the entry point, a toolbox for supporting the product sustainable development is designed by this research, which guides users to select the feasible state-of-art tools and provides a comprehensive framework with a standard set of environmental performance indicators. The assessment results will be able to apply into improvement activities for companies by employing these support tools. Companies using this toolbox will be able to benchmark within firms and competitors, and link with other advanced production methods, or initiatives and guidance in order to improve competitiveness**.**

5.2. Existing toolboxes related to sustainable production

Based on extensive investigation, there are two existing toolboxes demonstrating the similar concept discussed in this study. OECD Sustainable Manufacturing Toolbox (OECD n.d.) is a web site that offers a comprehensive sustainable manufacturing performance improvement methodology. The tools offered in this toolbox site include: OECD sustainable manufacturing indicators that is a set of custom environmental impact categories covering water, energy, renewable energy, greenhouse gas, residuals, air, water releases and natural land; a spreadsheet format based datasets to calculate these indicators; tools for data collection and calculation that are introduced in the toolbox site but is not accessible for no reasons. Therefore, this toolbox is essential as a platform to introduce a new environmental impact performance measurement methodology and to offer custom data collection and calculation tools. Additionally, generic technical advice is provided based on the calculation results. However, the reliability and validity of this new methodology and datasets are not demonstrated based on the the examination towards the toolbox site and related publications.

U.S. National Renewable Energy Laboratory (NREL n.d.) introduced a LCA related sources toolbox. This toolbox introduces a wide range of tools applied in LCA practices including LCA software tools, and information related to LCA research institutes and journals. This toolbox almost covers all the existing LCA software and acts as an important toolbox for LCA practices. However, LCA related tools can only help users to identify environmental related challenges, and applying the LCA results into real sustainable production activities requires other supported tools.

The developed Sustainable Production Support Toolbox include a broad of validated and acclaimed tools and methodologies in research and industrial fields. Additionally, Life Cycle Inventory database tools, Environmental Management Scheme tools, regulation and directive tools, ISO standards tools are also included in this toolbox, in order to provide a comprehensive overview of main sustainable production activities including ecodesign, environmental performance measurement and reporting, recycling/reusing etc.

The key novelty of this toolbox is that it integrated all these included tools into the product development processes, by selecting the feasible tools from this toolbox, a sustainable product is able to develop, which is demonstrated in Chapter 9 by reporting a sustainable flooring product development process. The following sections will present an overview of the included tools and their application requirements and scope, with these tools' selection rules or frameworks.

5.3. Components of the toolbox

5.3.1. LCA software tools

This section aims to clarify the features of the mature LCA software used in the research and industry context, in order to identify appropriate application scenarios for this LCA software. Apart from the LCA software presented in this section, there are other types of LCA software, such as, Farm Carbon Calculator, which performs analysis on greenhouse gas emissions and carbon sequestration related to farm business (Hillier et al. 2011), and eToolLCD is a LCA and design software in the field of sustainable buildings and produces comprehensive sustainability reports complete with comparable sustainable building data (Díaz & Antön 2014). Given the key objectives of this study, only the LCA software can be used in the general scenario that is investigated.

SimaPro is the major LCA software aimed at LCA experts, and it helps the user to implement the modelling of products and product systems from a life cycle perspective. The user can create the product system by linking elements in databases, or inputting specific data, based on a functional unit (PRé 2015). The software is based on ISO 14040/14044 standards, and it allows building parametric modelling, thus allowing modelling of different types of relationships and displaying them in the scenario analysis.

GaBi is a software aimed at engineers, designers and LCA consultants for highly detailed modelling and assessment of the environmental impact of general product system (product, process or activity) produced worldwide. It offers GaBi database containing over 10,000 datasets at the time 2016, and this software is based on ISO 14040 and PAS 2050 standards. Its features include advanced balancing, advanced parameter functions, extended allocation (Herrmann & Moltesen 2015). GaBi offers graphical modelling and alternative environmental materials in the software interfaces, and life cycle engineering (LCE), Life Cycle Costing (LCC), and Life Cycle Sustainability (LCS).

openLCA is a software aimed at research institutes, SMEs and LCA consultants for detailed modelling and assessment of the environmental impact of all kinds of the product system. It offers a complementary database management platform, openLCA Nexus, which allows users to search any sources of LCA datasets, or purchase a commercial database from this platform. Its unique feature is that it is a free open-source LCA software, and the software is fully transparent as the source code is available online for free. The relatively new and unique feature introduced by openLCA 1.5 in 2016 is the functionality of handling Geographic Information System (GIS) data. The software is also based on ISO 14040 standard. Two types of calculation mode are provided by openLCA: the quick model and the analysis model.

Umberto aims at engineers and LCA consultants with high/low expertise (depending on versions) for highly detailed modelling and assessment of material and energy flow systems produced worldwide. This software has four versions: Umberto NXT CO2, Umberto NXT LCA, Umberto NXT Efficiency, Umberto NXT Universal. The main differences between these versions relate to the scale of database, and application fields. Umberto NXT CO2 and Umberto NXT Efficiency are software packages that are developed for applying in the CO2 based research, and the available database is mainly related to GWP data v2.2. Umberto NXT LCA and Umberto NXT Universal are suitable for the general LCA related research, and the provided database is the ecoinvent versions.

SolidWorks 2015 is a well-known 3D modelling CAD software, and a sustainability package is embedded that offers the screening-level LCA on both parts and assemblies. CML and TRACI are the only methodologies provided in SolidWorks 2015, and the impact categories presented with the carbon footprint, air impact, water impact, and energy consumption, which is not comprehensive for in-depth analysis. Moreover, CAD modelling is required to complete before assessing the sustainability performance. The package offers a comparison function for alternative materials used in the component to help users to identify sustainable materials. This tool also has the function of producing assessment reports including basic parameters of modelling objectives, pie charts and bar charts presenting analytical results. GaBi database provides datasets for this software package and SolidWorks 2015 in compliance with ISO 14040 standard.

Quantis SUITE 2.0 is a web-based LCA software set aimed at LCA consultants, and it supports users in transforming LCA results into decisions, action plans and added value (Humbert et al. 2012). The product version only performs carbon footprint assessment using the LCA approach and offers dynamic environmental analysis. The corporate version examines GHG emissions and the water footprint caused by the corporate activities. The main feature of Quantis packages is to evaluate the environmental impact from the perspective of the supply chain.

Sustainable Minds is a web-based software aimed at designers with low expertise in modelling and environmental impact assessment of the product. It contains its a custom database that is evolved from the ecoinvent and NREL North American Life Cycle Inventory databases. The tool defines life cycle stages as materials, processes, use, transportation and end of life, and users are not allowed to create new stages or sub-stages for the analysed targets, but alternative environmental materials are suggested in the presentation tab for analytical results. This software complies with the ISO 14040 standard.

The supported or embedded database and methodologies for the these investigated LCA software are presented in Table 5.1.

5.3.2. LCI database tools

Within the inventory analysis level, for every process of the flow crossing the product system needs to be specified in order to create the starting point of the assessment. In many cases, this process requires using third-party databases to create a complete LCI to describe the performance of product processes and stages. This section offers an overview of major LCI databases and their formats, in order to clarify general rules applicable to the database selection.

LCI databases have various characteristics, for instance, ecoinvent is a professional and widely used LCI database (Weidema et al. 2013), World-Food LCA Database is a sector based database, and the European Reference Life Cycle Database (ELCD) provides data collecting from front-running EU-level business associations. The investigated LCI database and their features are presented in Table 5.2.

The data format of the ecoinvent is named EcoSpold, and the main LCA software (e.g. SimaPro, openLCA) accepts this format. Apart from EcoSpold, the International Reference Life Cycle Data System (ILCD) format was introduced by the European Commission in 2005, along with the European Reference Life Cycle Database (ELCD). Some national or sector-based organisations also archive life cycle inventory data, e.g. the World Food LCA database (WFLDB) and Material Flow Accounts, and the data format of these databases are usually spreadsheet based, which are not supported by LCA software to import, therefore LCA practitioners are required to convert the data format into the EcoSpold or ILCD format, or manually input values through the software interfaces after data quality examination.

Table 5.1. The databases and methodologies offered by the LCA software

Software	***Database***	***Methods***	
SimaPro 8.0 (desktop)	ecoinvent ELCD EU & DK Input Output Database Industry data 2.0 LCA Food DK USLCI Agri-footprint Swiss Input Output Database USA Input Output Database	CML Eco-indicator 99 Ecological Scarcity 2006 EDIP 2003 IMPACT 2002+ ReCiPe USEtox 2.0 BEES + TRACI 2.1	Water footprint Cumulative energy demand Ecological footprint Ecosystem damage potential Greenhouse Gas Protocol IPCC 2013 EPD 2013 EPS 2000 ILCD 2011 Midpoint+
GaBi 6.0 (desktop)	GaBi databases ecoinvent U.S. LCI database ELCD Data on demand service	CML 2001 Eco-indicator 99 EDIP IMPACT 2002+ EDIP 2003 ILCD	ReCiPe TRACI 2.1 USEtox AADP IPCC AR5 Ecological Scarcity Method 2006
Umberto 7.11 (desktop)	Umberto NXT LCA Umberto NXT Universal ecoinvent GaBi EstiMol	ReCiPe Impact 2002+ Eco-indicator 99 CML	TRACI IPCC
openLCA 1.5 (desktop)	PSILCA ecoinvent Social Hotspots ProBas GaBi Database Agribalys Ökobau.dat LCI-Inventories.ch NEEDS ELCD Bioenergiedat USDA	CML Eco-indicator 99 Ecological Scarcity Method 2006 Cumulative Energy Demand	ILCD 2011 ReCiPe TRACI 2.1 USEtox

SolidWorks 2015 (desktop)	GaBi database	CML TRACI	
Sustainable Minds (web)	Expanded from ecoinvent, USLCI	SM 2013, uses TRACI 2.1 impact categories	
Quantis SUITE 2.0 (web)	ecoinvent 2.2 Quantis SUITE Water footprint database World food LCI database	Carbon footprint GHG Water footprint IMPACT 2002+	

Table.5.2. LCI database and their features

Databases	***Features***
Ecoinvent	It comprises LCI data from the energy, transport, building materials, chemicals, paper and pulp, waste treatment and agricultural sectors, based on the Swiss and European demand patterns (PRé 2015).
GaBi	It includes all relevant information in view of the data quality and scope of the application of the respective LCI result / data set, and the data is presented with the referenced functional unit (Chiu & Chu 2012).
World Food LCA Database (WFLDB)	WFLDB represents agricultural primary products and processed food products, and it assists companies and environmental authorities in processes of eco-design of food products and Environmental Product Declarations (EPD) (Whittaker et al. 2013).
European reference Life Cycle Database (ELCD)	ELCD comprises LCI data from EU business associations and other sources for key materials, energy carriers, transport, and waste management (Garraín et al. 2015).
EXIOBASE	It is a spreadsheet based database that can be used for the analysis of the environmental impacts associated with the final consumption of product groups (Wood et al. 2015).
Global Emission Model for Integrated Systems (GEMIS)	GEMIS covers processes for energy, materials, and transport, as well as recycling and waste treatment processes. Material processes are based on EU data, transport processes are based on EU and US data. (Skarvelis-Kazakos et al. 2009).
U.S. life cycle inventory database	It serves as a central repository for information about the total energy and resource impacts of developing and using various commercial building materials, components, and assemblies (PRé 2015).
Chinese Core Life Cycle Database (CLCD)	CLCD provides data of more than 600 unit processes ranging from energy, metal/non-metal, chemicals, to transportation and waste treatment. The main data resources are government or industrial statistics and calculated based on ingredients and batch formula (Li et al. 2013).
Material flow accounts	It is a database contributed by Eurostat’s material flow accounts results, and it presents flow accounts framework by estimating the material footprints of the goods consumed in the EU (Wiedmann et al. 2015).
DataSmart	It is a database of the North American region, and it is developed through expanding USLCI data, ecoinvent v2.2 data, in addition, over 700 processes covering textiles, packaging, biomaterials, dairy industries, U.S. state electricity mixes are included (EarthShift 2015).

5.3.3. Environmental management scheme tools

The Environmental Management Scheme (EMS) refers to a series of strategic approaches in which a company can mitigate its impact on the natural environment. These approaches relate to its internal activities including environmental policy, planning, implementing, and corrective action (T. Feng et al. 2014), and EMS is an increasingly important tool for companies to reduce environmental impacts and increase competitiveness in sustainable production (Lam et al. 2011). Two major environmental management schemes are widely adopted globally: The Eco-management and Audit Scheme (EMAS) and ISO 14001. This section will identify differences between the two EMSs, and discuss their links to the LCA and the sustainable production activities.

The latest version of the EMAS scheme is regulated by the European Regulation EC 1221/2009, and it is a sustainable development strategy of the European Commission. As a result, EMAS is more rigorous than ISO 14001 regarding the implementation. There are many regulations legislated by the European Commission to support the development of EMAS, for instance, Directive 2009/125/EC introduces the ecodesign requirements; Directive 2014/52/EC defines the environmental impact assessment procedures.

ISO 14001 is created by the International Organization for Standardization, and its main aim is to provide a framework for a holistic and strategic approach for an organisation for setting its environmental policy, plans, and actions (Zobel 2013; Curkovic & Sroufe 2011; Heras Saizarbitoria & Boiral 2013). ISO also introduces many standards for improving EMS performance for registered organisations, for instance, ISO 14031 (Evaluating environmental performance) and ISO 14020 (Environmental labels and declarations) provide guidance on the design and use of environmental performance assessment, and the principles of establishing environmental labels and declarations, respectively.

5.3.4. ISO 14000 standard tools

The ISO 14000 series are designed to enable worldwide adoption of sustainable production and cover environmental aspects of organisations' activities in terms of identifying problems, controlling impact and monitoring performance. This section offers an overview of the major standards of ISO 14000 series and aims to clarify the link between standards and other tools (e.g. regulations and directives) that support sustainable production. The investigated ISO 14000 collection standards and their summary are presented in Table 5.3.

The investigation results show that the ISO 14000 series are closely linked with regulations and directives related to environmental improvement in terms of evaluation methodologies and implementation. For instance, the BSI (British Standards Institution) standard PAS 2050:2011 was created within the framework of ISO 14040 and ISO 14044 to offer a consistent approach for measuring the greenhouse gas (GHG) emissions occurring from goods and services (Kulak et al. 2013; Jeswani et al. 2013). Moreover, ISO 14020 introduces an effective way of influencing consumers' purchasing decisions through environmental labels and declarations that provide information about the environmental characteristics of a product or service (Finkbeiner 2013). Furthermore, the EU Regulation NO 66/2010 and Directive 2010/30/EC requests to apply this methodology to several specific product types of high energy consumption, with standardised rating classes in the EU State Members, which sustain the energy efficiency improvement at a higher level, and ensure the regulating results are easily understood by consumers.

Within the LCA framework, the standards of the ISO 14000 series are linked with LCA methodologies through compliance with common environmental impact categories/indicators, for instance, ISO 14046 and ISO 14064 introduce guidelines and requirements on how to assess the water footprint and carbon footprint of organizations' activities, and these assessment methodologies are also adopted by the main LCA software tools (e.g. SimaPro, GaBi).

Eco-labelling and declarations are widely used to certificate products or services' environmental performance in order to influence consumers' green consumption behaviour and companies' sustainable production. For the present, there are some schemes and initiatives on the market that offer an assessment of products' carbon footprint. The regulatory rule in the European Union market is Regulation (EC) No 66/2010 (Eco-label Regulation), and it has been adopted by the major large businesses. Most carbon footprint certification tools, whether by a third party or a company working on their products, relies on a range of LCA approaches and data. There are many possible approaches, and therefore outcomes, when implementing LCA analysis, for instance: The Carbon Reduction Institute offers carbon neutral certification schemes; the non-profit association, Climatop, provides labelling for climate-friendly products; Carbon Trust certification provides solutions for improving environmental sustainability.

Table 5.3. Main standard tools of ISO 14000 series and their summaries

Standards	***Summary***
ISO 14001 - Environmental Management System	It is established as a voluntary standard to support environmental protection and prevent pollution through monitoring organization’s environmental activities. The inventory analysis introduced in this standard requests standardized data sets for industrial process (Zobel 2013; To & Lee 2014; Testa et al. 2014).
ISO 14006 - Guidelines for Incorporating Eco-design	It provides guidance on how to incorporate environmental aspects into product design within the framework of environment management systems and quality management systems (Lewandowska & Matuszak-Flejszman 2014).
ISO 14020 - Environmental Labels and Declarations	It is established to compliance with ISO standards in the development of Environmental Product Declarations (EPD), eco-labels for utilization of business-to-business communication (Finkbeiner 2011; Pastor et al. 2014).
ISO 14031 - Environmental Performance Evaluation	It gives guidance on the design and use of environmental performance evaluation within an organization. It is established with intention to apply to all organizations regardless of type, size and complexity (O'Reilly 2000; Feldman 2012).
ISO 14040 - Life Cycle Assessment Principles and Framework	It considers the entire life cycle of the product, encompassing the extraction and processing of raw materials, manufacturing, distribution, use, recycling and final disposal and allows to obtain environmental indicators obtained for each impact category or to obtain a single indicator grouping all the impact categories considered (ISO 2006a).
ISO 14044 - Life Cycle Assessment Requirements and Guidelines	It introduces guidelines on conducting LCA studies that provide an organization with information on how to reduce the overall environmental impact of its products and services (ISO 2006b).
ISO 14046 - Water Footprint Principles, Requirements and Guidelines	It introduces specification of water footprint assessment of products within the framework of life cycle assessment, and it defines the requirements and guidelines on how to report the water footprint assessment results (ISO 2014).
ISO 14064 - Greenhouse Gases	It introduces specifications on how to quantifying, monitoring organizations’ greenhouse gas emissions, reporting emissions performance and validating the performance results (Johnson 2009; Bastianoni et al. 2014).

5.3.5. Directive and regulation tools

The increasing importance of regulatory rules in sustainable production is being recognised and is supported by many scholars (Casamayor & Su 2013; Gibson et al. 2013; Zailani et al. 2013). Based on the findings of extensive review towards the latest versions of EU regulations and directives, it has been found that the current EU regulations and directives related to sustainable development are mainly built on the following directions: environmental emissions (e.g. 2014/52/EC), ecodesign (e.g. 2009/125/EC), labelling (e.g. 2010/30/EC), disposal/waste management (e.g. 2011/65/EC). Within this context, the LCA framework is an efficient measurement tool for assessing the implementation performance of these regulatory tools. Furthermore, the outcomes of these regulations and directives contribute to the improvement of sustainable production and mitigate the challenges (e.g. data quality and uncertainty) associated with the LCA. This section will present the overview of the regulations and directives and their applicable scopes with the aim of producing some considerations and rules enabling users to select feasible regulations and directives guiding and improving the sustainable production activities. The reviewed regulations and directives and their summaries are presented in Table 5.4.

Table 5.4. Summaries of the EU directives and regulations for sustainable production

Directives & Regulations	***Summary***
Directive 2008/98/EC - Waste Framework Directive	It builds a legal framework for treating waster in the EU. The directive introduces recycling and recovery targets to be achieved by 2020 for household waste (50%) and construction and demolition waste (70%) (European Commission 2008).
Regulation (EC) No 1221/2009 - Eco-Management and Audit Scheme	It is created to provide the highest quality instrument for the voluntary evaluation, reporting and improvement of environmental performances (European Commission 2009c).
Directive 2009/125/EC - Ecodesign Directive	Its objective is to establish a framework for the setting of ecodesign requirements for energy-related products, and it applies throughout the products' life cycle, from manufacture, use, and until their end of life (European Commission 2009a).
Directive 2010/30/EC - Energy Labelling Directive	It extends the directive scope from energy using products to energy related products. The directive requires that appliances be labelled to show their power consumption, and introduces new energy efficiency classes (A+, A++ and A+++), in addition to A-G ratings (European Commission 2010a).
Regulation (EC) No 66/2010 - Eco-Label Regulation	It requests the label awarded to all goods or services distributed, consumed or used on the Community market. The general criteria are based on the environmental performance of products, and potential to reduce environmental impact (European Commission 2009b).
Directive 2010/75/EU – Industrial Emissions Directive (IED)	It is the main EU instrument regulating pollutant emissions, and it introduces five initiatives: an integrated approach preventing pollution; use of best available techniques (BAT); strict emission limit values; inspection system; more participation for the public (European Commission 2010b).
Directive 2011/65/EC - RoHS Directive	The directive is on the restriction of utilisation of six hazardous substances in electrical and electronic equipment. This directive has been extended to apply all electrical and electronic equipment (EEE) (European Commission 2011b).
Directive 2012/19/EC - Waste Electrical and Electronic Equipment (WEEE) Directive	It requires changes throughout the Electrical and Electronic Equipment (EEE) product cycle, including improved product design to ease dismantling, recycling, and reuse (European Commission 2012a).
Directive 2014/52/EC - Environmental Impact Assessment (EIA) Directive	Its objectives are to simplify the procedures for assessing environmental impact, define timeframes for the different stages of environmental assessment, improve the quality, transparency of EIA reports (European Commission 2014).

The Waste Framework Directive encourages the transfer of waste into a secondary raw material and explains how to distinguish between waste and by products (Arends et al. 2015; Manfredi & Pant 2013). The Directive sets two new recycling and recovery targets to be achieved by 2020: 50% preparing for re-use and recycling of certain waste materials from households, and 70% preparing for re-use, recycling and another recovery of construction and demolition waste (European Commission 2008). However, the directive has not introduced many strong policies to prevent potential waste damage.

The Ecodesign Directive is only applied to energy-related products and requires that only products that may be sold in the EU (Tu et al. 2013; Sanyé-Mengual et al. 2014; Van der Velden et al. 2015). It defines the principles, conditions and criteria for implementing ecodesign instead of creating mandatory terms for products. Furthermore, these conditions and criteria are established with the focus on environmental characteristics of products or services, which include energy, water waste, and lifespan, in order to increase environmental performance efficiently.

Energy Labelling is a voluntary scheme that has been created to regulate the products of high level of environmental impact (Heinzle & Wüstenhagen 2012; Broberg & Kaaukauskas 2014; Ruester 2016). All products introduced by the Ecodesign Directive are required to attach the energy label, and products that have adopted this directive to date include lighting equipment, air conditioners, TVs, tumble dryers, washing machines, dishwashers and refrigeration equipment (European Commission 2009a). Eco-label regulation closely collaborates with Energy Labelling, and it awards products with high environmental performance in the market, and it is a voluntary and selective scheme to lead the production and consumption market in the sustainable direction. For the present, it covers 28 product and service categories, and their certification criteria apply to the entire life cycle of the product or service.

The RoHS Directive and the WEEE Directive are closely linked in terms of implementation, as the WEEE Directive is designed to identify and replace hazardous substances defined by RoHS for companies in the existing production, and the hazardous substances for the present are: lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls, polybrominated diphenyl ethers (European Commission 2011b). Furthermore, the WEEE Directive has the strict disposal, recycle, and reuse rules for electrical and electronic products, which not only affect the refinement of production procedures and materials but also require companies' investments to meet these requirements.

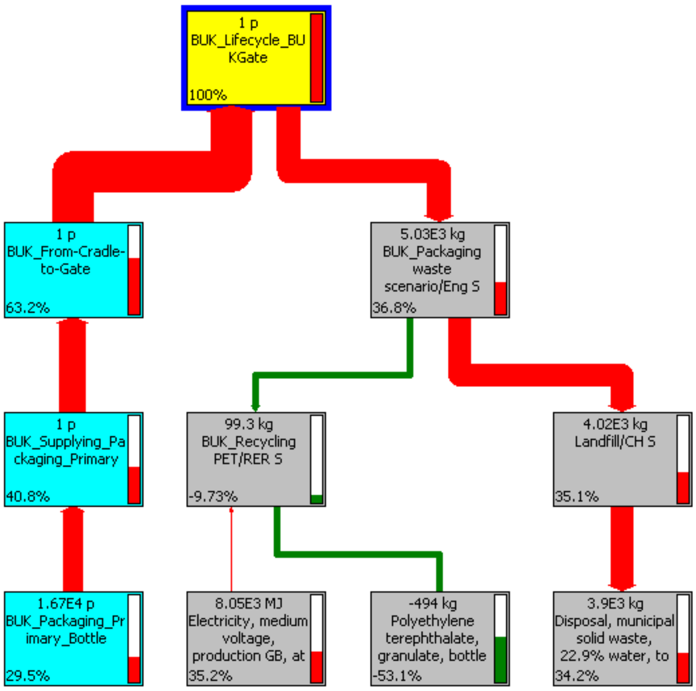
The key challenge of the Environmental Impact Directive is that it cannot enforce environmental requirements in the stage of a product's life cycle (Smart et al. 2014; Anker 2014), and it only offers an overall target of environmental impact reduction. Also, the environmental impact indicators for industries are not introduced in the existing Directives, which remains the difficulties in building a consistent environmental reporting framework and improving reporting transparency. The Industrial Emissions Directive promotes the use of BAT (Best Available Techniques) to assess environmental impact, and LCA is the only methodology that supports the environmental impact assessment (Cikankowitz & Laforest 2013). In addition, the IED only specify environmental impacts caused by the overall productions, which causes difficulties in quantifying the environmental contribution related to companies' production activities.

5.4. The tool selection considerations

Desktop and Web-based LCA software tools

The performance of desktop LCA software is more powerful than web-based LCA software regarding the database scale and presentations of analytical results. Desktop LCA software usually provides more than one database for users to choose from depending on requirements of study objectives or product features. In addition, there is no web-based LCA software that offers the Sankey diagram (see Figure 5.1) to present analytic results for the presence; however, this issue is addressed within this research by developing an Internet-based LCA system, which is a novelty (For more information about the system development please see Chapter 7). The major benefits of the Sankey diagram are that it clearly reflects the hierarchy and weighting of environmental impacts caused by the processes, substances and stages for the product life cycle, which is convenient for users to identify the main environmental burden, so that mitigating solutions can be created with clear objectives. An example of Sankey diagram is presented in Figure 5.1.

Figure 5.1. An example for Sankey diagram showing product materials contribution



Among these desktop-based LCA tools, there are no major differences in terms of user interfaces. The user interfaces are designed and presented following the basic sequences of product life cycle, and each interface allows users to input information and values related to a stage or a process. Additionally, all desktop-based LCA software allows users to import new databases and LCA methods files.

openLCA offers the possibility of developing customised functions as its source code is publically available, and users can access these through re-programming its source code. SimaPro provides a commercial developer version for users to extend its functions into other platforms. The customised/developer service is only available in these two LCA software.

The user interfaces of web-based LCA software are more intuitive than desktop LCA software. Web-based technologies provide access to all used data stored on the server, enabling users to perform collaborative LCA work and to access the software and data from different physical locations. Due to the limitations of web related technologies, web-based LCA software is not as competitive as the desktop-based LCA software in terms of the size of databases. Moreover, the function of importing or creating new LCA methods are not provided by web-based LCA software. Currently, web-based LCA software is suitable for LCA users who need simple analytic results or users who do not have a strong LCA background. After successfully incorporating large-size professional database and enabling more powerful LCA methods which often exist in the Desktop LCA software, the Web-based LCA will be equally applicable for experienced users.

Life cycle inventory database tools

LCI databases may contain missing data or uncertainties. Most missing data can be filled through examining statistics from relevant reports, utilising commercial database, or conducting independent studies (Suh et al. 2013). In the case of using data from multiple data sources, a framework examining data quality is introduced by ISO 14040/44 standards, and the quality indicators include: time-related coverage, geographical coverage, technology coverage, precision, completeness, representativeness, consistency, reproducibility, sources of the data, and uncertainty (ISO 2006a; ISO 2006b). This framework sets the minimum requirements for LCA practitioners to assess the fitness and quality of the selected data. In addition, the review findings show that there is not a common data format accepted by the LCI databases and LCA software, so the users have to convert various data format into an accepted format supported by the selected LCA software, which remains a barrier to improve the efficiency of LCA practices.

Environmental management scheme tools

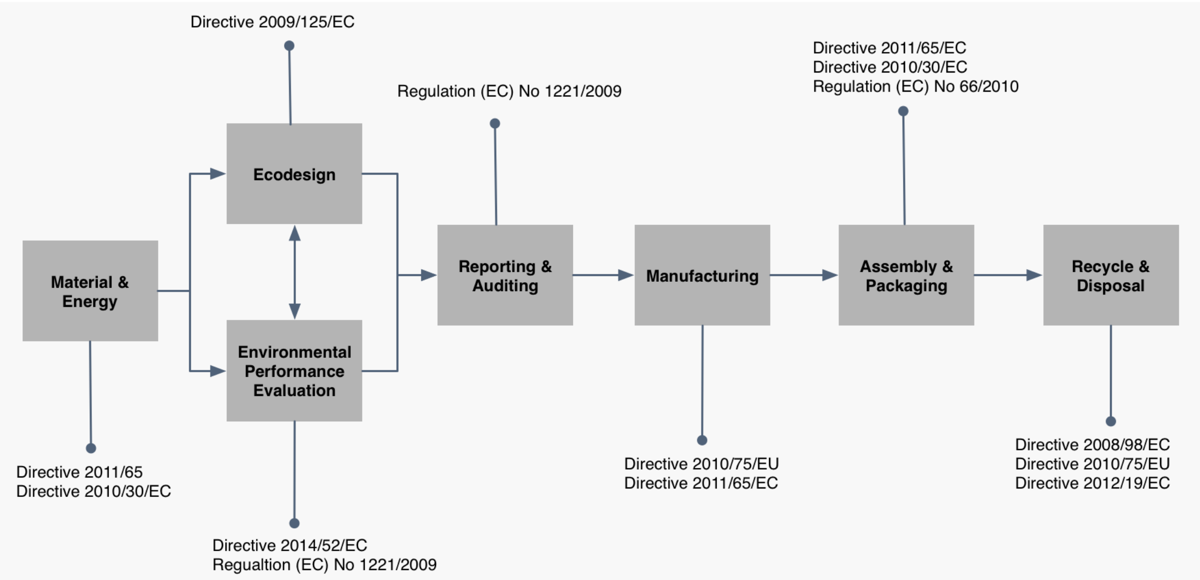
The research investigation findings show that environmental management scheme (EMS) requires registered organisations to achieve continuous improvement in environmental performance, while the ISO 14001 requires periodic improvement, which is the major difference between them. There are also many minor differences in terms of practical standards or procedures, for instance, EMAS requests all the details related to organisations' verified performance to be publicly available, while the ISO 14001 only requires the environmental policy to be publicly available.

The relationship between EMAS and ISO 14001 is reciprocal, and the EU has created requested modifications to encourage ISO 14001 registered organisations to meet EMAS requirements in the EU Member States. However, it is essential to note that both systems offer overall environmental improvement targets and guidelines in main corporate activities, but solutions are addressing specific practical issues are not provided. In addition, both systems require organisations to conduct LCA and environmental performance reporting, but the issues of data uncertainty and data missing are not addressed within the ISO 14001 system. The European Commission has started to address these challenges through legislating regulations to improve the data quality and transparency, for instance, the Directive 2010/75/EC clearly defines the average emission limit values and minimum and maximum time for sampling polluting substances (European Commission 2010b).

The directive and regulation tools

How to explore and apply the benefits of these directives and regulations to production practices is a complex task, as it is affected by many other factors including the company's scale, their needs and practical enforcements. The key regulations and directives in the EU market have been discussed, and these regulatory rules' application scope in production activities through a sustainable product life cycle is demonstrated in Figure 5.2. The requirements of these regulations and directives are updated on a regular basis, and the implementation should follow latest amendment versions.

Figure 5.2. Selection of the directives and regulations underpinned sustainable production in the EU



5.5. The toolbox development

Resulting from the myEcoCost project supported by the European Commission Seventh Framework programme, a Sustainable Production Support Toolbox (SPST) has been developed, where the investigated tools and techniques have been included. The toolbox is installed in the LCA server that provides detailed, technical guidance for the users to select the feasible tools for their particular applications in sustainable production.

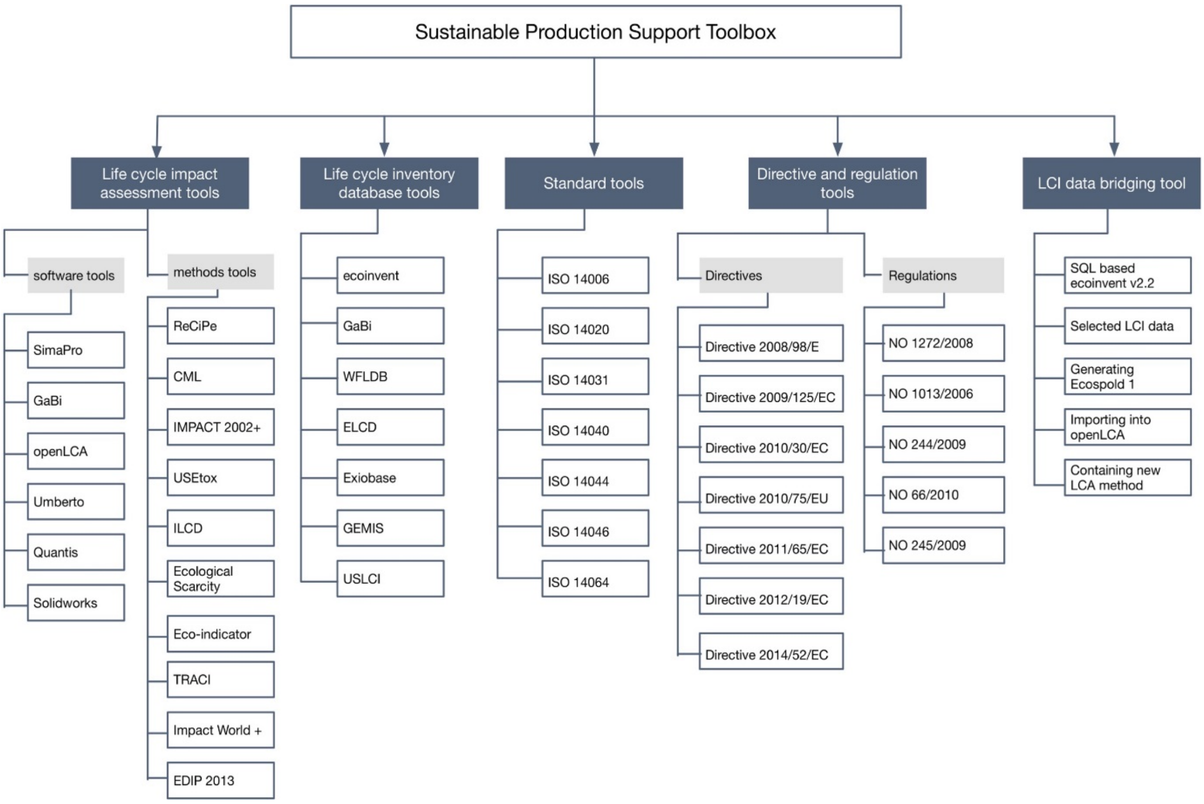
5.5.1. The integrated toolbox overviews

The integrated toolbox for sustainable production support is a dedicated application providing information for users to support sustainable production at different stages of the product life cycle. This toolbox applies the essence of the LCA calculation results into key principles or instructions to help users deliver economic and social benefit outcomes. According to the aims and definition of toolbox presented above, multiple features have been taken into account:

- existing methods and tools, which will support the calculation and decision making for sustainable production related to LCA.
- considering the sophisticated needs from the professional users in terms of selecting desirable data and conveying it into specific sustainable strategies.
- considering the non-professionals' needs in the acquisition of ecoCost information associated with a specific product or service.
- supporting the comprehension of constitutive indicators through the entire toolbox user experience.

According to the application scope and attributes of these tools, a structure of this toolbox is depicted in Figure 5.3. This integrated toolbox has been developed to help end-users select feasible tools, and employ the analytic results of the calculation into the practices for improving the product sustainable performance. There are five modules/tools in this toolbox, which are detailed as follows:

Figure 5.3. The overall structure of sustainable production support toolbox



<u>(1) Life cycle impact assessment module</u>

This module is to present the main LCA software tools that are specialised in calculating environmental impact through the product life-cycle, such as SimaPro, Sustainable Mind. Moreover, the LCA methods are also presented in the form of the web page, including ReCiPe, CML, ILCD, etc. The LCA software and method contained in this module almost covers all the professional LCA software, and validated LCA methods. Some emerging LCA methods (e.g. IMPACT World+) are reviewed in Chapter 2 but are not contained in this toolbox module as they are required to further validate by LCA professionals from academic and industry.

(2) Life cycle inventory database module

This module only comprises the latest information of well-known LCI databases such as Ecoinvent, Gabi databases, and ELCD. Data of product life cycle are crucial elements to the results of the life cycle assessment. The accuracy and applicability of the LCI results depend on the data provided by LCI database. Different databases focus on particular regions and specific areas. Moreover, guidelines for selection and utilisation of such databases have been discussed in Section 5.4.

(3) Standard module

ISO standard tools are contained in this module, and these standards enable sustainable development and cover environmental aspects of organisations' activities in terms of identifying problems, controlling impacts and monitoring performance. Except for the ISO series, other standard tools are included: Guidelines for Incorporating Eco-design (Lewandowska & Matuszak-Flejszman 2014), Environmental Labels and Declarations (Finkbeiner 2013; Pastor et al. 2014), Environmental Performance Evaluation (O'Reilly 2000), Greenhouse Gases (Bastianoni et al. 2014). These standard tools need to collaborate with these regulation tools to ensure company production activities to meet regulating requirements.

(4) Directives and regulation module

This module mainly presents the requirements and application scope of directives and regulations related to sustainable production activities in the EU. The contained regulatory tools cover all the product development process, for example, Direct 2009/125/EC promotes eco-design products, and introducing schemes for encouraging eco-design companies. The intention of establishing this module is to help users, particularly smaller companies to better understand the environmental requirements from regulating departments.

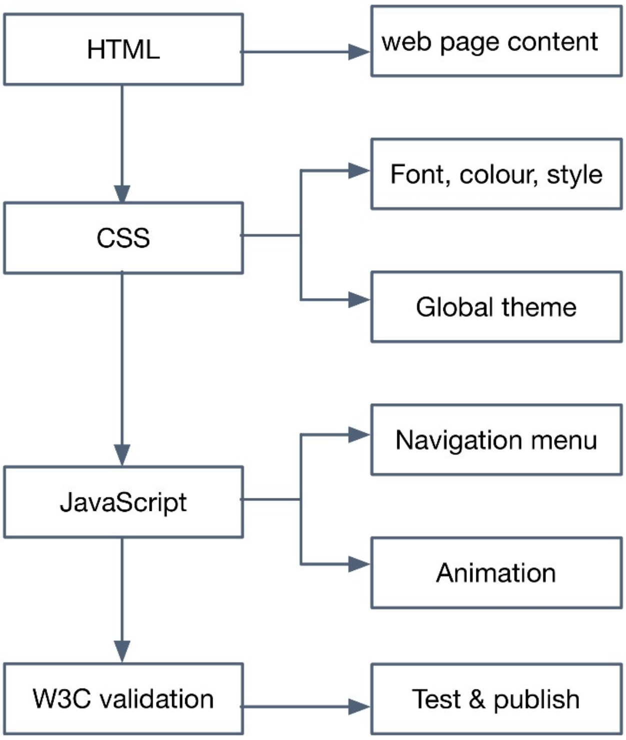
(5) Life cycle inventory data bridging tool

This module contains two major packages, including the novel myEcoCost method files; and a LCI data bridging GUI application, which helps users to call 'GetProduct' and 'GetElementaryFlow' API functions in the LCA server to acquire data from SQL format ecoinvent database, and collect direct inputs from users to supplement the data required by standard format of EcoSpold file. The details of this GUI tool will be reported in Chapter 7.

5.5.2. The integrated toolbox development

This sustainable production support toolbox is a web based application, and its development process involves the application of HTML, CSS, JavaScript technologies. The software used to develop this toolbox is Dreamweaver. Figure 5.4 shows the flowchart for developing this application and the adopted technologies, which are described in the following sub-sections:

Figure 5.4. The flowchart for sustainable production support toolbox development



(1) Implementation of HTML

Hyper Text Markup Language (HTML) is widely used in the web application development, which aims to display the contents on a web page, and improve the performance of complex elements in the web page (e.g. media application), and handle the interoperability related to HTML documents (W3C n.d.).

Text and tags are the main two main elements in HTML document, which describes the document content and defines the layout and attributes of the document contents, respectively. A <html> tag encloses the document head section and body section, and they are marked by the <head> and <body> tags, respectively. The head is used by developers to define the document name and parameters for the web browser to render the document. The body presents the actual HTML contents. While tags are used to define the attributes of the document elements, for example, defining the background of the contents, or hot spots that link the document elements to other documents. An example showing these main elements of a HTML file is shown in Figure 5.5.

Figure 5.5. An example of HTML file showing the toolbox index page

```html
<!DOCTYPE html PUBLIC "-//W3C//DTD XHTML 1.0 Transitional//EN"
"http://www.w3.org/TR/xhtml1/DTD/xhtml1-transitional.dtd">
<html xmlns="http://www.w3.org/1999/xhtml" lang="en" xml:lang="en">
  <head>
    <meta http-equiv="Content-Type" content="text/html; charset=utf-8" />
    <meta name="robots" content="index, follow">
    <meta name="google-site-verification"
    content="I8jV_Tx8KUN6KL9s1xWW0YYGfZKcOygzZU48ASSFG3o" />
    <script src="https://www.google.com/jsapi" type="text/javascript"></script>
    <title>index</title>
  </head>
<body>
            <li>Home</li>
            <li>Life Cycle Impact Assessment Tools</li>
            <li>Life Cycle Inventory Database Tools</li>
            <li>Standard Tools</li>
            <li>Directive and Regulation Tools</li>
            <li>LCI Data BridgingTools</li>
</body>
</html>
```

(2) Implementation of CSS

Cascading Style Sheets (CSS) is the technology for controlling the presentation of web page elements, including colour, font, etc. (W3C n.d.), which usually collaborates with HTML to define the web page overall style. Compared with HTML, CSS has a few more features: providing a wider selection of colours and fonts; handling the presentation effects for all the tags. Furthermore, the CSS enables more flexible web presentation, for example, using CSS text-indent approach to indent paragraphs instead of applying HTML tags, (<pre>). Figure 5.6 demonstrates an example of applying paragraph indentation.

Figure 5.6. An example for using CSS control web page presentation

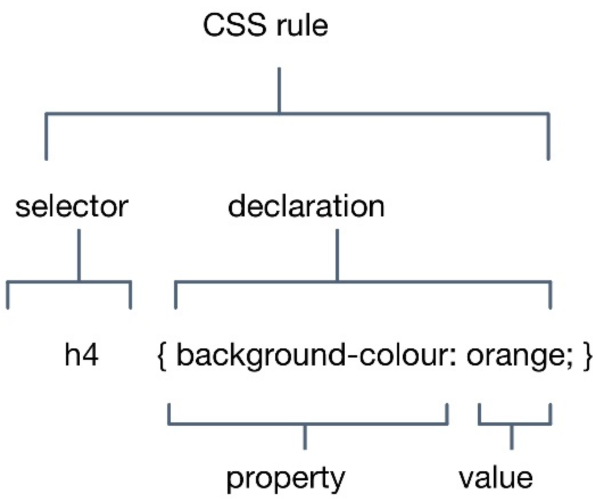
```
  </head>
  <style>
    p (text-indent: 20px;)
    h4 (text-indent: 30%;)
  </style>
<body>
  <p>These intermediate endpoint categories have been grouped into the three areas of protection:
  Human Health, Resources and Ecosystems.</p>

  <h4>Normation and weighting of ReCiPe 8 endpoint</h4>
</body>
</html>
```

CSS uses rules to control the appearance of the page. The rules are usually compiled in a separate document instead of the content page including the HTML elements. The CSS rule consists of two components, which is described as following, and their internal relations is presented in Figure 5.7:

- A selector to indicate the document elements are under control.
- Declarations indicating the properties of an element, such as its typeface or colour, or font.

Figure 5.7. An example of CSS rule structure



All the CSS files are processed by the browser that follows documents' declaration to retrieve and invoke CSS rules simultaneously. Once the CSS files are rendered by the browse, they are cached in the web browser's memory for implementation to the following pages.

CSS are used in this toolbox to define the presentation of fonts, tables, lists, colours. Six files consist of the CSS documents for this toolbox, which are described as following:

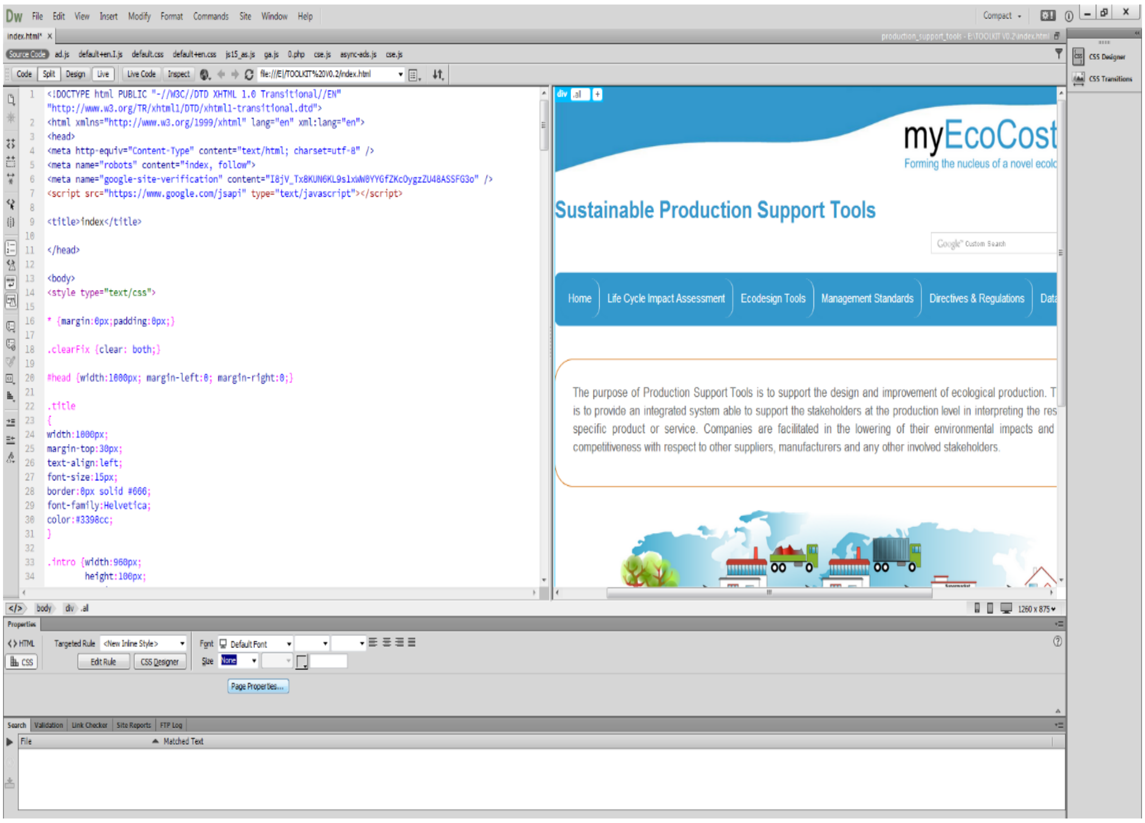
- **Font-awesome folder**: It contains the complete details of the fonts in the theme. It contains four subfolders: CSS, FONTS, LESS, SCSS, which contains the CSS files exclusively dedicated to the font used in the toolbox web pages.
- **Fonts folder**: It contains the fonts and its source to be used in the web page theme when the administrator changes the font. Most of the fonts are web based fonts with extensions 'EOT' and 'SVG'.
- **Default.CSS**: This CSS file handles the style of all the webpages and the location of various menu and submenus. Also, it holds the information on colours, figure adjustments and other information related to the margins and its value.
- **Fonts.CSS**: This CSS file is also the information on fonts but manage to change the whole website theme.
- **Layout.CSS**: This CSS file enables the theme to be responsive in order to adapt different screen sizes. Also, it contains the gaps and inter-level spacing of the paragraphs, the lines and figures.
- **Media-queries.CSS**: This CSS file allows the website to link the email queries that are directly linked to the website.

(3) JavaScript implementation

There are two types of web page processing: implementation compiled application programs and executing them on the web platform, or invoking the web browser to interpret and implement scripts within the HTML web page. The method of implementing scripts is applied to develop the sustainable production support toolbox.

JavaScript is client side code embedded within HTML documents, which is marked by a script tag that helps browser detect this is the scripting code. These commands declared by the JavaScript is implemented by the browser. The JavaScript scripting language is primarily used for creating interactive features on the Toolbox web page, for example, clicking page navigation menu, popping dialogue menu. The Java Script is edited through Dreamweaver software alongside with HTML and CSS, as shown in Figure 5.8.

Figure 5.8. A screenshot of Dreamweaver showing the HTML, JavaScript and CSS compiling



jQuery is a lightweight JavaScript library, used to control HTML events, animations and other interactions on a web page, which is applied in the toolbox development. Usually, JavaScript can be added to an HTML page in two ways: using script tags to delimit the JavaScript codes in the HTML document; placing all JavaScript codes in an individual file and linking to it by applying a script tag. However, the code is needed place into a separate file to link to it if the code file of a large scale, which will avoid downloading all the code file for every time web visit. For the first method, the JavaScript code is placed between the > and < characters, right before " ", which presented in Figure 5.9.

Figure 5.9. An example showing the navigation implementation by using JavaScript

```
<script type="text/javascript">
jQuery(window).scroll(function() {
  if (jQuery(this).scrollTop() > 220) {
    jQuery("#nav").css({"position": "fixed", "top": 0, "width": "1024px"});
  } else {
    jQuery("#nav").removeAttr("style");
  }
});
</script>
```

5.5.3. Validation of the integrated toolbox

The web-based toolbox was developed to compatible to the mainstream of web browsers across multiple platforms. The presentation of web pages may vary, depending on the web browser versions, which can affect the website design performance. To test the developed toolbox, three implementation documents presented above are required to test, which are described as following:

- HTML Validation: Using the Markup Validation Service (W3C n.d.) provided by the W3C ensure there is no errors with these sites. This includes all the web pages either with the same templates, or using different templates
- CSS Validation - Using CSS Validation Service (W3C n.d.) provided by the W3C to certify all the CSS files belonged to the toolbox perform designed functions. All the style sheets for the web page are tested, which include layout.CSS, style.CSS and printer.CSS.
- The toolbox documents were stored in a commercial website hosting platform, which has an operating system security applied to it using Apache and HTTP access.

The evaluation results show that the designed sustainable production support toolbox is successfully developed and performs the designed functions. The screenshots of the toolbox interfaces are presented in Figure 5.10.

Figure 5.10. A screenshot of the toolbox interfaces in Safari browser.

5.6. Summary

Compared with the existing toolboxes which are investigated in the literature, there is no sustainable production support toolbox available which includes all the dominated tools and validated techniques in the research and industry fields. To overcome this problem, this chapter presents a toolbox which includes state-of-the-art technologies and tools in the field of LCA and sustainable production, and this toolbox offers information for users to support sustainable production at different stages of the product lifecycle. This toolbox enables end users to elaborate the analytic results of LCIA into key principles or instructions to deliver economic and social benefit outcomes. The toolbox developed by this research is able to integrate with the general product development, to help stakeholders to apply sustainability technologies into the production and related stages in product lifecycle, which is a novel contribution for the sustainable productions.

Chapter 6: Life cycle inventory management system for data bridging (LCIMS-DB)

6.1. Introduction

LCA research has a history of more than two decades, and the life cycle inventory databases have strongly improved regarding the number of processes, the geographical representativeness and the scale of datasets, but data quality is still one of the most important problems. As any LCA can only deliver a snapshot of the status quo at the time of analysis, even the best ones fail to provide up-to-date data at any given time; consequently, much of the life cycle data available and used in the assessments is out-dated (Geibler et al. 2013). Another problem is the diversity of methodologies, as data may have been estimated using differing assumptions, data sources and system boundaries, assumptions which make it difficult to compare results from different LCA studies. Product specific primary data is often missing, and general data from life cycle inventory databases (e.g. ecoinvent) has to be used instead. Therefore, a flexible and powerful tool is required to implement the retrieve and delivery for the LCI datasets.

The existing LCA software (e.g. SimaPro, GaBi) are well-developed in both theoretical and practical levels, but they still rely on the desktop-based software environments. The main reason is that the existing LCI databases are designed and created for the desktop software environment, particularly the commercial LCI database, ecoinvent, provides the XML format based data, which is known as EcoSpold 1 and EcoSpold 2. This data format could not provide flexible data management functions within the web-based system and application operating environment.

In order to sever the proposed web-based product environmental performance evaluation system, the LCI database is required to convert into SQL (Structured Query Language). SQL are designed to allow the user to have full manipulation capability of the data in the relational database and to play an intermediate role between computer programs and the relational database. Furthermore, SQL is the basic way to interact with a relational database. The user formulates a query from a list of commands understandable by the relational database management system (RDBMS).

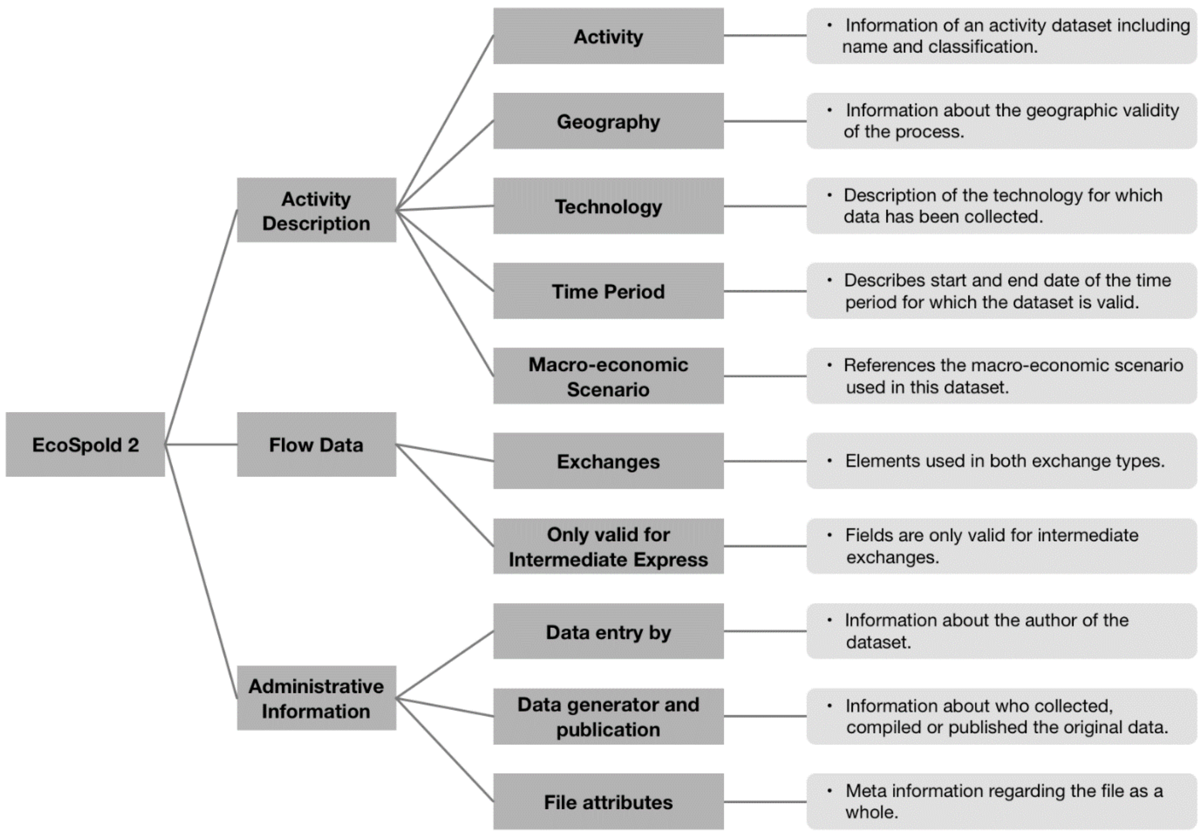
In this research, the ecoinvent database is applied to convert into SQL database, as it is the widely used LCI database in the LCA software. This chapter will introduce the method to implement the data format conversion, a LCI data management framework, the development of a GUI application executing data bridging functions.

6.2. Development of SQL based ecoinvent database

6.2.1. ecoinvent database formats: EcoSpold1 and EcoSpold2

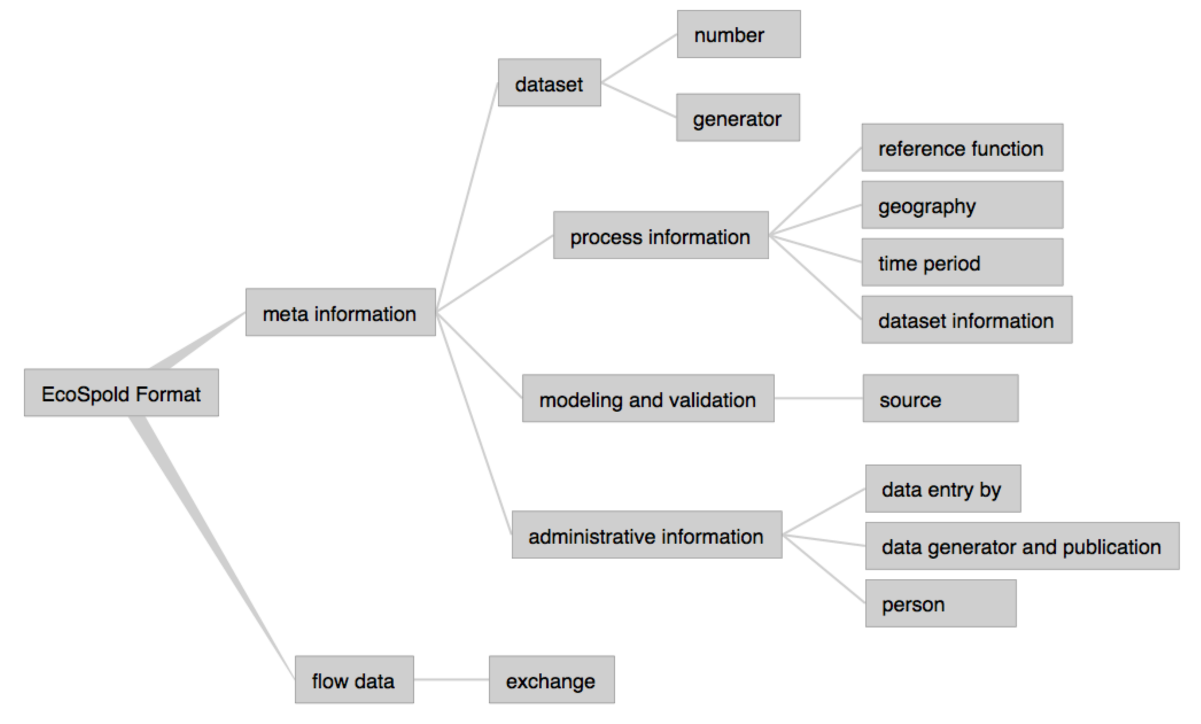
EcoSpold1 was introduced in 2000, and its latest version, EcoSpold2, was launched with ecoinvent version 3 in 2013. EcoSpold1 and EcoSpold2 are essentially an XML (extended markup language) format file, and they have evolved from the international SPOLD data exchange format (Frischknecht & Rebitzer 2005) and international technical specification ISO/TS 14048. Each EcoSpold format file presents information and values of processes and substances. Compared with the EcoSpold1, Ecospold2 includes many new sections, such as 'mathematical relation' and 'variable names'. The literature investigation shows that the default EcoSpold2 format file is systematically and hierarchically built with 233 data types, but not all of the data types are needed to implement a LCA. The required data types are filtered from the default EcoSpold2 schema documentation, and their top-level structure is depicted in Figure 6.1. Through examining the requirements of each data section, it is clear that the central data section is 'Activity Description' (see Figure 6.1), which records functional units, values, country codes of processes, and flow properties.

Figure.6.1. The compulsory data sections of EcoSpold2 format file and their high-level structure (The contents refer for EcoSpold2 Documentation (ecoinvent 2013))



The structure of a standard EcoSpold1 format is depicted in Figure 6.2, and the role of each component is also presented in the Figure 6.2. The key component in EcoSpold1 format is the ‘process information’ that records the functional units, values, category and subcategory of flow data, which is the main figures used to implement a LCA calculation.

Figure 6.2. The structure of EcoSpold1 format file (the structure refers (Frischknecht & Rebitzer 2005)



The ecoinvent centre offers a free tool, EcoEditor, which is developed to create, edit, review and upload EcoSpold1 and EcoSpold2 format files (E et al. 2013). Additionally, this tool supports the format conversion between EcoSpold1 and EcoSpold2 format files.

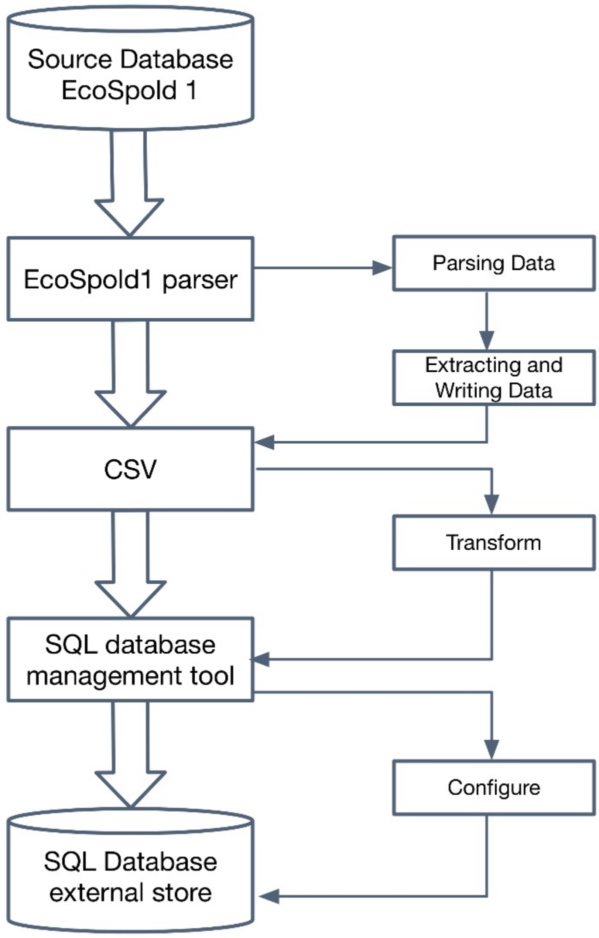
LCI databases (including ecoinvent) may contain missing data or uncertainties. Most missing data can be filled through examining statistics from relevant reports, utilising commercial database, or conducting independent studies (Suh et al. 2013). In the case of using data from multiple data sources, a framework examining data quality is introduced by ISO 14040/44 standards, and the quality indicators include: time-related coverage, geographical coverage, technology coverage, precision, completeness, representativeness, consistency, reproducibility, sources of the data, and uncertainty (ISO 2006a; ISO 2006b). This framework sets the minimum requirements for LCA practitioners to assess the fitness and quality of the selected data. Also, the review findings show that there is not a common data format accepted by the LCI databases and LCA software, so LCI data format conversion is still a barrier to improving the efficiency of LCA practices. The following section will introduce methods to convert EcoSpold format files into SQL format, which is the most standard database format for software engineering.

6.2.2. Converting ecoinvent database into SQL database

Due to the availability of ecoinvent database licence, ecoinvent database v2.2 was selected to demonstrate the conversion. The ecoinvent v2.2 data set format is EcoSpold1. Although there are differences between EcoSpold1 and EcoSpold2 in terms format components, the introduced method is still applicable to convert EcoSpod2 to SQL format. The suggested method is to use EcoEditor tool to convert EcoSpold2 to EcoSpold1, then to employ the following method.

The following section addresses a novel method converting EcoSpold 1 into SQL database management tool. The conversion will utilise a script implementing the EcoSpold1 data parsing and extraction, and a SQL database management tool. The process of implementing this method is illustrated in Figure 6.3.

Figure 6.3. The conversion framework from EcoSpold1 to SQL

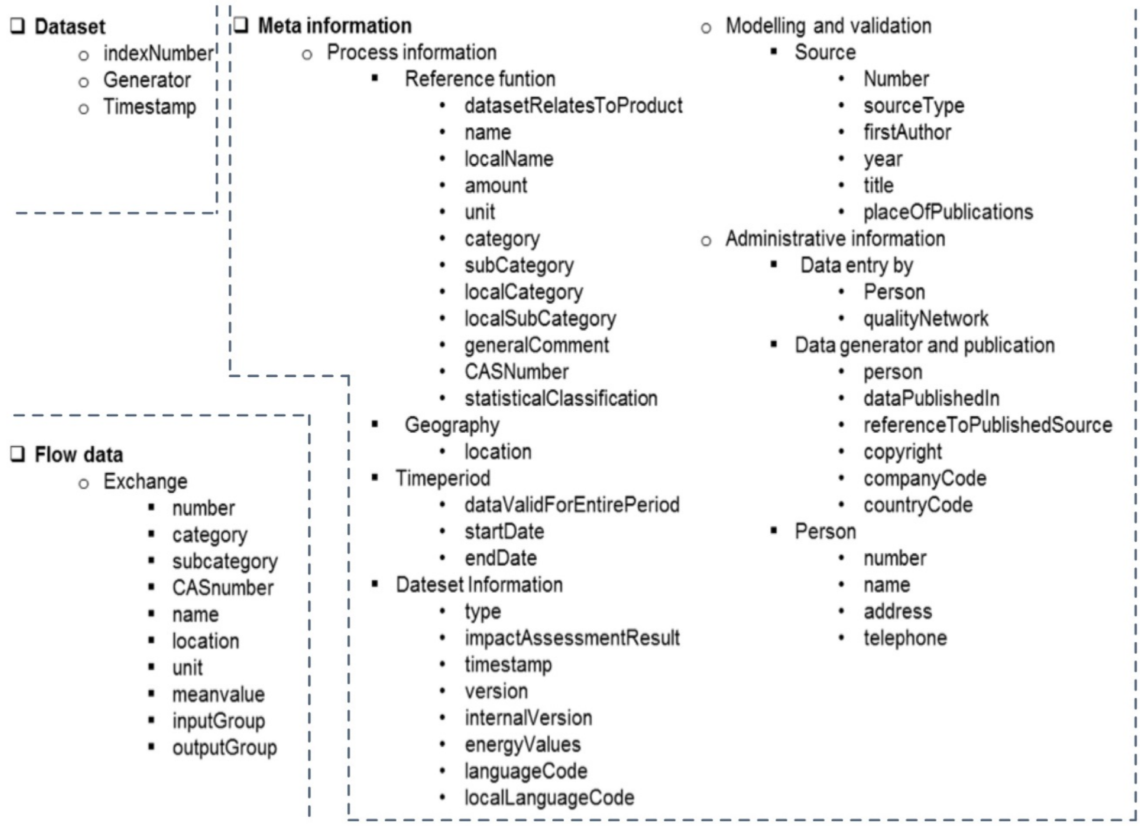


EcoSpold1 Parsing:

In ecoinvent v2.2, there are 4087 EcoSpold1 files, and each of them has the same data structure, which records the information and values of processes and substances. For a single EcoSpold1 file, there are three main data components, which are presented in Figure 6.4, and are described as following:

- Dataset: contains initial information about one system process.
- Meta information: contains information about the process, modelling assumptions, validation details and administration.
- Flow data: contains information about inputs and outputs flows and information about allocation.

Figure 6.4. EcoSpold1 data elements ((Hischier et al. 2010))



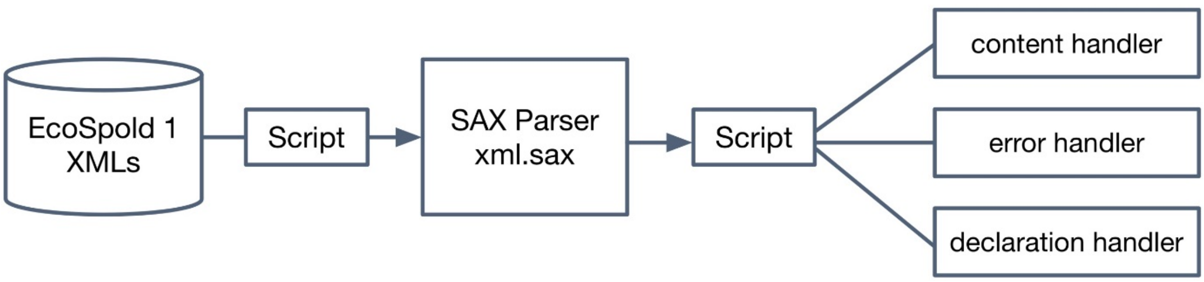
In order to extract all the datasets in each file, it is required parse each EcoSpold1 file. As the EcoSpold1 is compiled by XML language (see discussion in Section 6.2.1), the method for parsing XML file is applied.

In order to obtain the information and values contained in the XML file, the XML file is required to be handled by software that can recognises the data structure, and provide functions to implement other data format declarations. Two techniques are mainly applied in order to implement XML processing: Event based method and Tree-based method.

The event-based method is a stream-oriented technique that supports the user to access the XML contents sequentially. Simple API for XML (SAX) is the standard developed in different languages (e.g. Python, Java) (SAX n.d.), which handles XML file without constructing computer memory representation. Moreover, the user can define a set of call-back methods while a particular event occurs during the parsing. The Document Object Model (DOM) is a type of tree-based technique that supports users to generate a memory representation of an XML file (Consortium 2004). With DOM, every element of the XML file can be navigated and accessed. Therefore, SAX is suitable for straightforward XML parsing without considering the consumption of the computer resources, and DOM is suitable for complex XML parsing, for example, multiple extracting different data types in different XML files.

In the case of parsing EcoSpold1 files, SAX approach is used because all the data types that are required to parse and extract are same. Python language is applied in this research to implement the EcoSpold1 parsing and extracting. Xml.sax is a standard library in Python, which is designed to implement SAX method for XML file parsing. The process for implementation of EcoSpold1 parsing is illustrated in Figure 6.5.

Figure 6.5. The process for parsing EcoSpold1



As Figure 6.5 shown, in order to implement the xml.sax, Python script files are used. The full script is presented in Appendix 1, which was compiled in order to handle three functions, as following:

- Content handler: define the extracted data name, category and type.

- Error handler: define warning information and responses when the parser detects errors.
- Declaration handler: declare the path of source data, and path for storing extracted data.

In order to demonstrate the extracting process, a EcoSpold1 file (i.e. 00827.EcoSpold1) is presented in Figure 6.6, which shows 'MetaInformation' of the EcoSpold1 file. As Figure 6.6 shown, there are some data elements, including 'name', 'localName', 'infrastructureProcess', 'unit', 'category', 'subCategory', 'localCategory', 'localSubcategory', 'amount', 'includeProcessess', 'generalComment', 'inftrastructureIncluded', 'datasetRelatesToProduct', 'geography', and 'technology'.

Figure 6.6. Meta information of 00827.EcoSpold1


```
▼<metaInformation>
  ▼<processInformation>
     <referenceFunction name="packaging glass, white, at plant" localName="Verpackungsglas, weiss, ab Werk"
     infrastructureProcess="false" unit="kg" category="glass" subCategory="packaging" localCategory="Glas"
     localSubCategory="Verpackungsglas" amount="1" includedProcesses="This module includes the material and energy
     efforts for: preparation of the glass melt, melting furnace, feeder, container forming, cooling down, packaging.
     Transports for the input materials are included as well as direct emissions to air, waste water and waste."
     generalComment="A production site with a sorting capacity of 100 kt per year and a total life span of 50 a is
     assumed." infrastructureIncluded="true" datasetRelatesToProduct="true"/>
     <geography location="DE" text="average German situation, based on an industry survey"/>
     <technology text="Mix of really used technologies in Germany"/>
```


These structured data elements are contained in each EcoSpold1 file, in order to extract these data, a Python script is compiled, to apply the xml.sax library and extract the required data elements (see Appendix 1). The primary function of this script is to expand of each data element of the file with different conditional statements depending on the attribute of the date element. For each item, the script search for attributes and namespaces declarations. The data element is restructured to create a sequence of attribute element with value moved to a new output form. The function works recursively to transform data elements with nested children.

Transforming the extracted data into CSV file:

In the process of script implementation, EcoSpold1 file is analysed in order to extract knowledge required for the subsequent processes. Information and values regarding data elements types are extracted from the highly-structured EcoSpold1. Moreover, this process can automatically write the extracted data into a rationale form. In this step, Comma-Separated Values (CSV) form is applied (see Figure 6.7), as it is a common data exchange format that is widely accepted by database management tool. Therefore, this process is required in order to identify complex and simple types used in the specified CSV file. The data extraction process is involved in detecting basic types such as integers, decimal, bit-strings and others which can be mapped to a lower signed/unsigned CSV form.

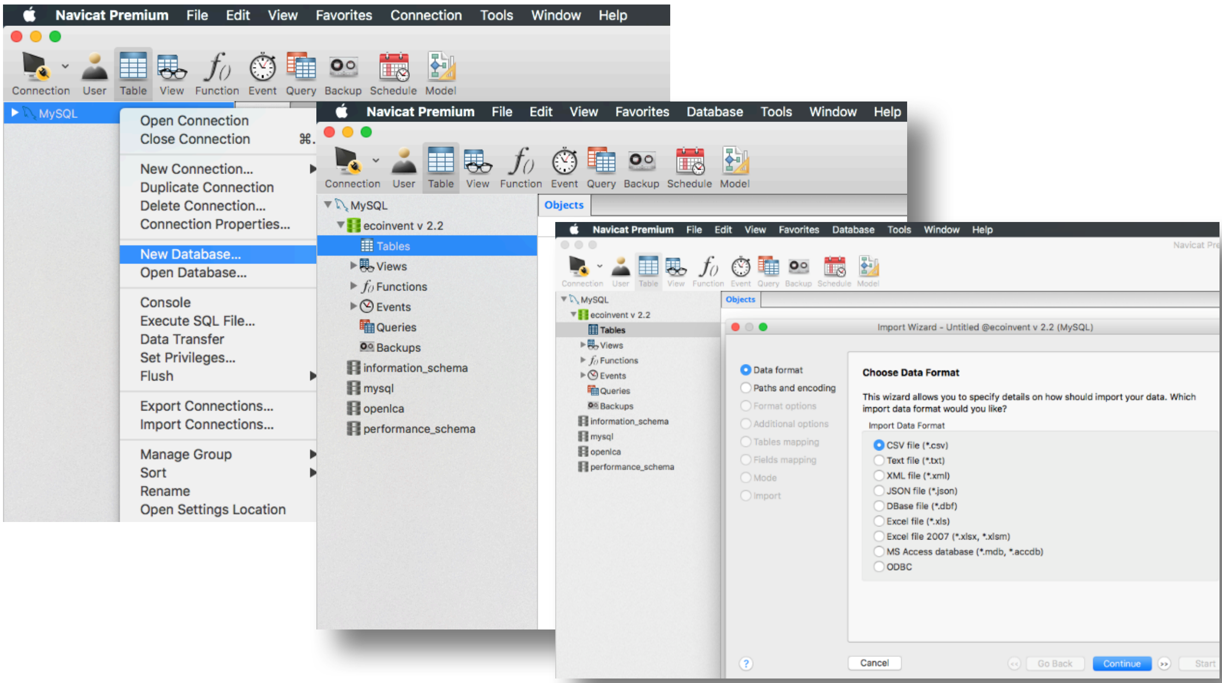
Figure 6.7. An example showing 00827.EcoSpold1 extracted information storing in CSV

id	category	subcategory	localname	meanvalue	unit		
826	glass	packaging	packaging glass, white, at plant	038902-17-3	kg	1	Cl
1381	natural gas	power plants	electricity, natural gas, at power plant	068333-17-3	kWh	1	IT
827	glass	packaging	packaging glass, white, at plant	065421-17-3	kg	1	D
828	glass	packaging	packaging glass, white, at plant	098711-17-3	kg	1	RI
829	glass	packaging	packaging glass, white, at regional storage	023891-17-3	kg	1	Cl
831	hard coal	fuels	hard coal briquettes, at plant	044597-17-4	MJ	1	RI

Importing the CSV into database management tool

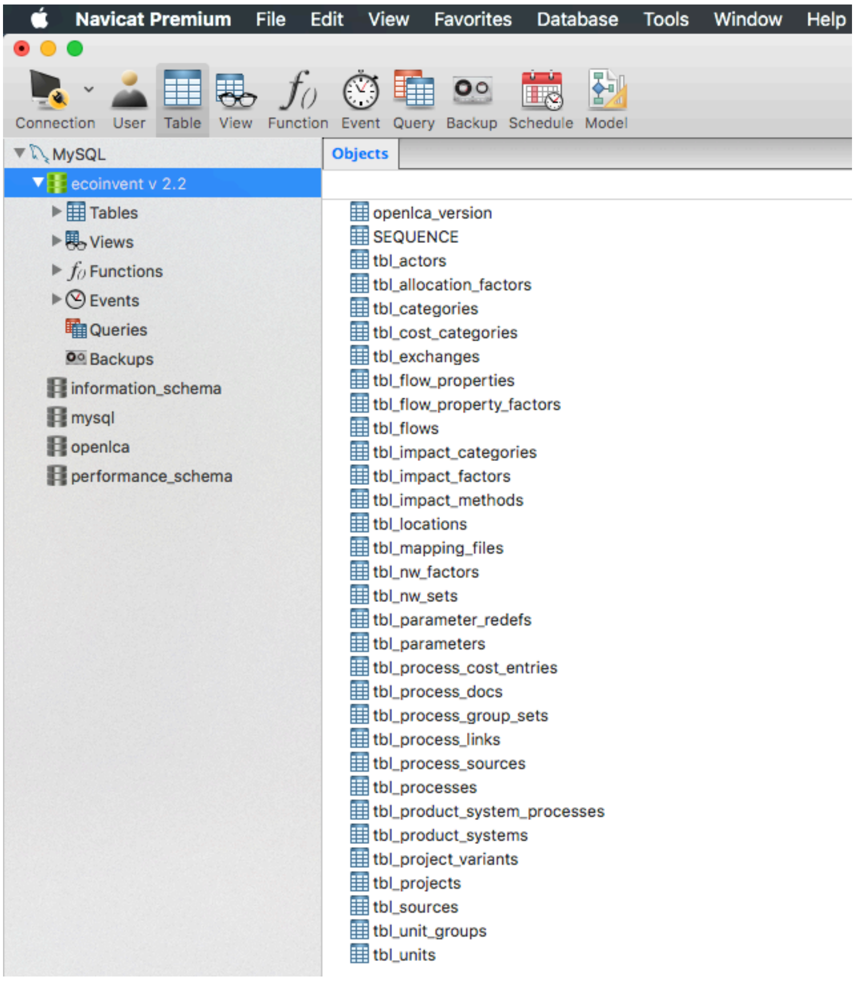
Once all of the 4087 EcoSpold1 files of ecoinvent v 2.2 are extracted into the CSV file, the CSV file is needed to import into a SQL database management tool. Navicat Premium (PremiumSoft n.d.) is applied in this study, which is a powerful database management tool as MySQL, PostgreSQL. It is a straightforward step to import the CSV file into the database management tool. As the Figure 6.8 shows, the user firstly creates a new database (namely, ecoinvent v2.2), then click 'tables' within the new database, and select the 'data format' as CSV.

Figure 6.8. Import the CSV file into the database management software



Once the CSV file imported into the Navicat, 32 tables extracted from ecoinvent v2.2 can be found, as Figure 6.9 shows. The 'tbl_processes' is the core table as it contains the figures and information regarding the flows and the processes. The relationship between the flows and processes are defined in 'tbl_categories' table, of which 'f_parent_category' column shows 'null' are flows, and the rest columns are processes.

Figure 6.9. A screenshot of Navicat Premium showing ecoinvent V2.2 SQL tables



Until this step, the ecoinvent v 2.2 has been successfully converted and imported into a SQL database management software. In order to use this SQL supported LCI database in other web applications, it is only required to configure the connection protocol between this database software and application servers, which is not reported in this section.

6.3. Development of the LCI data bridging tool

6.3.1. Overview of the tool

In order to export the SQL formatted LCI databases for serve other web applications or desktop based LCA software, a LCI data bridging GUI is proposed to achieve the data bridging functions. Except for the LCI datasets from the ecoinvent database, some product lifecycle data provided by the governmental departments or business associations can also be stored in the database, for example, UK statistics on waste (DEFRA 2015) is a spreadsheet based database that provides the waste statistics in the UK; one of the statistical categories is regarding the various packaging wastes, which is useful for the recycling scenario analysis for the LCA. This solution would be useful for users to retrieve and investigate the feasible LCI data when their required data is missing in the ecoinvent data. These stored LCI data need to convert into feasible data formats, in order to apply these stored LCI data in the professional LCA software and application. Hence, a LCI data bridging GUI is proposed to develop for users to select the required LCI data from the SQL database and export the data to required format.

On the other hand, users usually use these exported LCI data in the main LCA software and applications. Therefore, an investigation regarding the accepted data import formats of main LCA tools is conducted. The investigation results are presented in Table 6.1, which shows EcoSpold1 is the data format supported by all the LCA software.

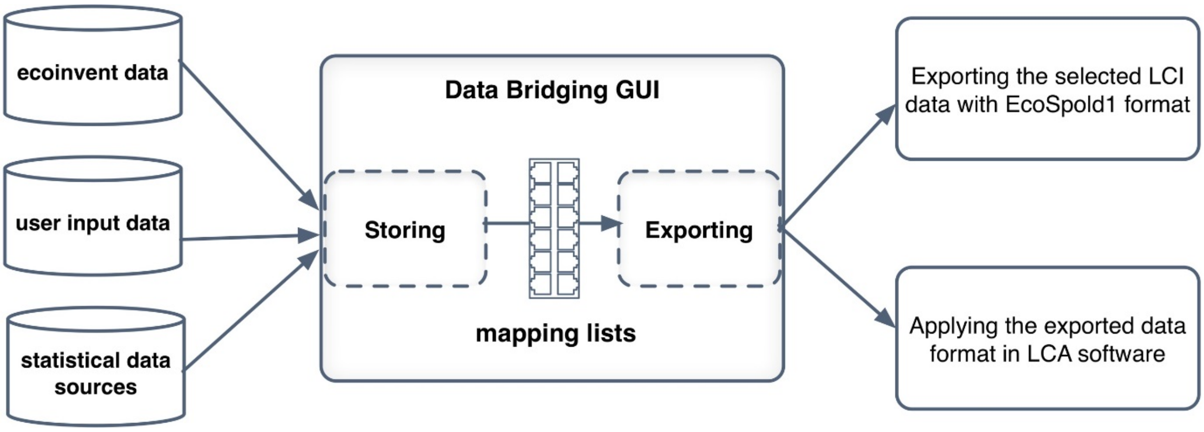
Table 6.1. Import and export formats accepted by LCA software

LCA software	***Import format***		***Export format***	
SimaPro 7.3	CSV EcoSpold v1	SimaPro	CSV EXCEL	TXT EcoSpold v1
Gabi 6	GBX GPR file	ILCD EcoSpold v1	GBX GPR file ILCD	EPD EcoSpold v1
OpenLCA 1.5	EcoSpold v1 & v2 Excel ILCD	SimaPro CSV ILCD ZOLCA	EcoSpold v2 Excel ILCD	EcoSpold1 JSON-LD
Umberto	Umberto project file		EXCEL, CSV	

Based on the discussions, the data flow for the proposed GUI application implementing data bridging function is depicted in Figure 6.10. The core functions of the data bridging GUI are described as follows:

- Export the selected LCI data in the a EcoSpold1 format file.
- Automatically applying the exported data in the LCA software tool.

Figure 6.10. A framework demonstrating the data bridging functions and data flow



As the exported data sets are formed as EcoSpold1 format, there is a mapping process forming the selected data elements and other relevant data sets. The mapping process is designed for users to define and select LCI data because the stored LCI data maybe need an update or modify to meet requirements of users' utilisation scenarios. There are four tasks involved in this mapping process:

- The data elements that are compulsory for LCA calculation will be selected by users and invoked from the database.
- The data information that is not compulsory for LCA calculation will not be displayed or set a default value in the exported data, in order to control the size of exported data format files. For example, the 'general comment' within the 'reference information' will not be able to export and only be viewing in the GUI interfaces.
- The data sets that need to be input or updated by users will be achieved in the GUI interfaces. For example, 'localName' is the relevant field in the EcoSpold 1 file. It is the local name of product and needs to be input by the user in the GUI interfaces.

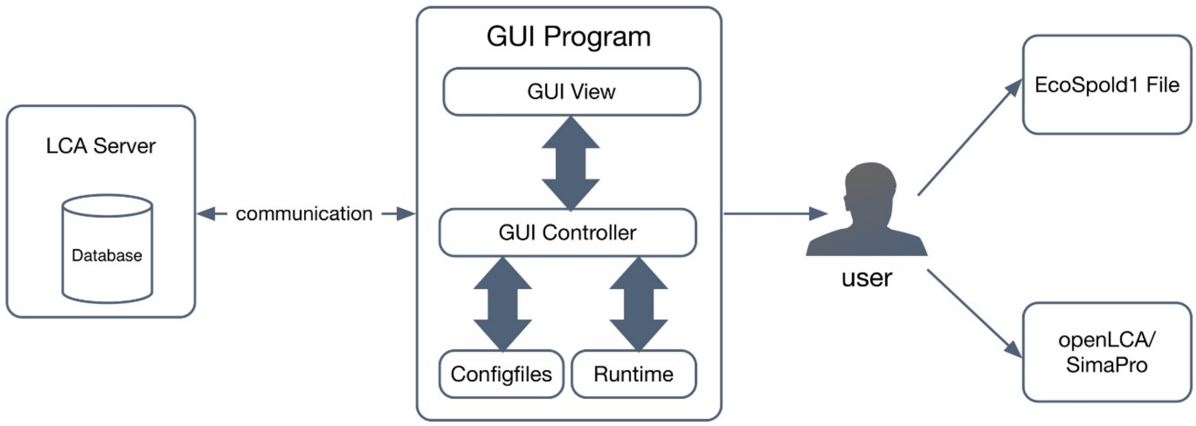
- The background information of exported data sets will be automatically defined by the GUI in the backend, for example, 'Today's date' indicates the date of the data exported from the database.

A table demonstrating these four data categories within an exported EcoSpold1 template is presented in Appendix 2, which clearly shows the contents of each data category and their data types.

6.3.2. Development of the tool components

Based on the above discussions, the data sets as required from the server and database is implemented by a GUI application. This GUI application is a Java package, and consist of a number of Java graphical components corresponding to LCI data mapping, communication and exporting processes. This involves a GUI communicate with server and database over the Internet. This GUI is developed with Java Swing package in Eclipse development platform. The architecture of the LCI data bridging GUI is presented in Figure 6.11.

Figure 6.11. The LCI data bridging GUI architecture



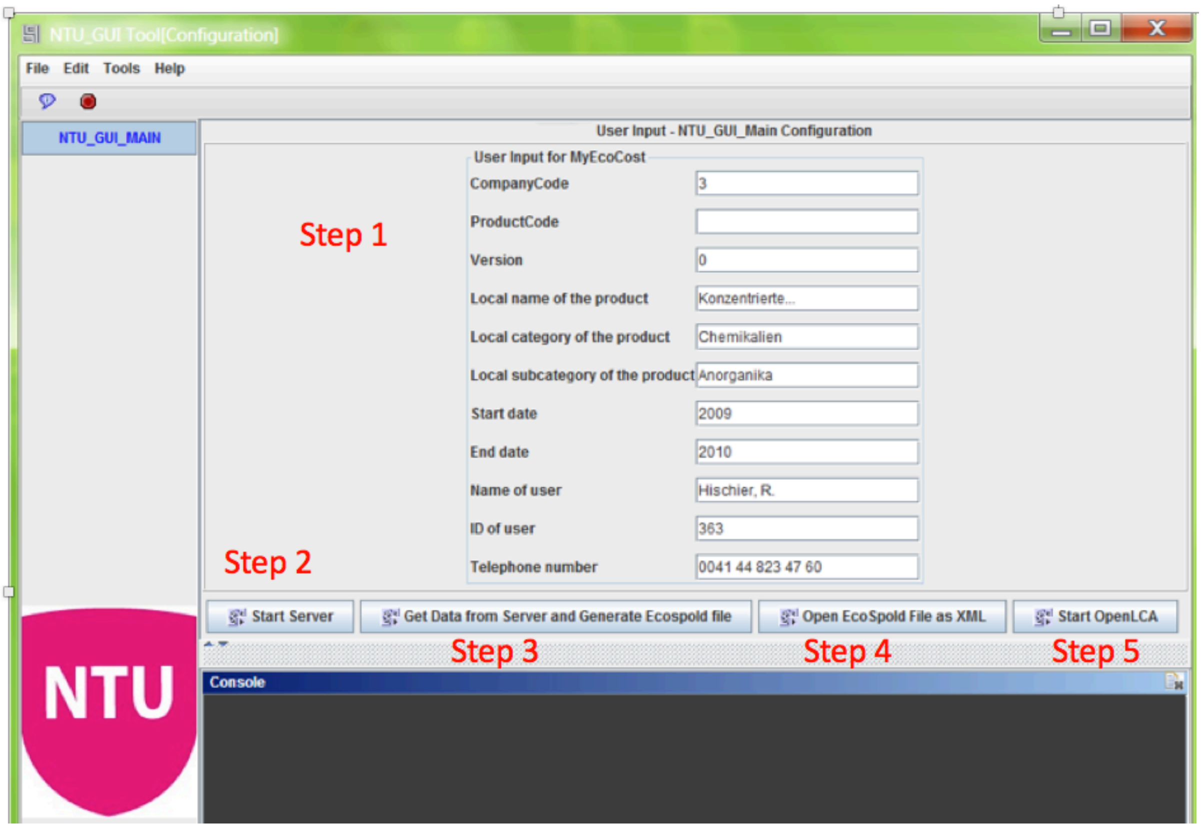
There are four main components in this GUI program, which are described as follows:

- The configuration files are written in XML, containing runtime assertions, settings of view components, communication message between the GUI controller and LCA server, database.

- Communication protocols are two-way message delivering communication between LCA server and GUI controller, which are also implemented by the GUI program package. Each event of user requesting LCI data from the server, is supported with the communication pattern, implemented both in the server side and GUI controller.
- The GUI controller is the central component of this application as it coordinates with all other components of the GUI program:
    - The controller reads the configuration file, which contains the specification of retrieving and inputting LCI data, and use it as guidance for mapping required LCI data elements, and generating EcoSpold1 files.
    - The controller communicates with the GUI view to support the interactions with users. It transmits data to the GUI view, and delivers users' commands and input-data to the server side.
    - The controller also coordinates a checking module in runtime that record runtime data about the Java program through this application. Users can use the configuration file modify the specific requirement, for example, what type of LCI data are visible/hidden.
- The runtime contains all the required package and libraries for running this GUI application.

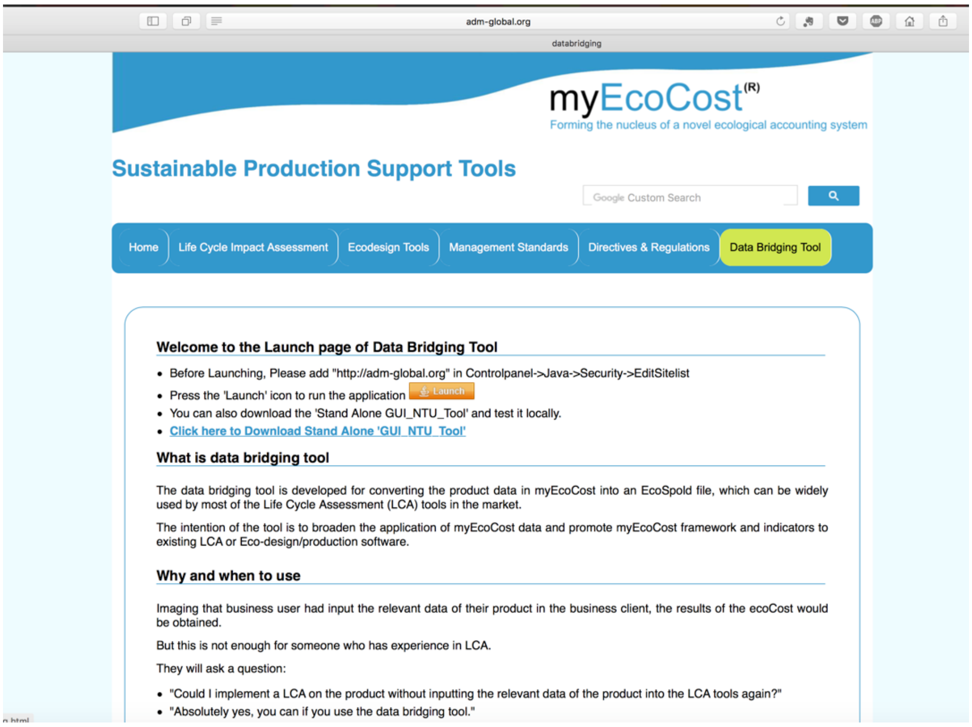
The connection is established through communication protocol declared in the GUI configure files, and the data bridging is performed to retrieve the requested data. Once the connection is established, the data is retrieved and stored in the local path where the GUI is being executed. The data retrieved and stored in the local is added with the user input from the GUI and created as an EcoSpold1 file. Once it is meet the requirements of the specified standards (i.e. EcoSpold1 data structure and standards), it can be imported to the OpenLCA software, and the LCA calculation is triggered. A screenshot of the GUI prototype is shown in Figure 6.12.

Figure 6.12. Interface of the GUI application



This LCIMS-DB GUI is a standalone package that is downloaded from Sustainable Production Support Toolbox (see Chapter 5), a screenshot of which is shown in Figure 6.13. After the installation of GUI, users can search the LCI data related to a product through searching the product's basic information, e.g. product name, product category, Invoice (see step 1). Once users confirm the requested LCI data, they need trigger the business server by clicking the 'Start Server' (see step 2), and send the LCI request by pushing 'Get Data from Server and Generated EcoSpold file' (see step 3). Then the user requested LCI data sets are automatically stored on the local computer in the form of EcoSpold1 format file, which is readable by the normal text editor (see step 4). This file describes the processes and resources involved in manufacturing this product. Moreover, this user custom defined EcoSpold1 file is accepted by the openLCA and SimaPro LCA software, and users can import this file into LCA software to conduct an independent environmental performance assessment on the product (see step 5).

Figure 6.13. The download page for the developed GUI application in the sustainable production support toolbox



6.4. A new LCA method in openLCA

A LCA method file is a group of parameters showing the environmental performance of the corresponding manufacturing process or materials, with scientific grouping and weighting logics (Frischknecht et al. 2009). openLCA provides interfaces for users to create new LCA methods. Once a LCA method is successfully defined and created in the software, it can be exported as a EcoSpold format based files (including EcoSpold1 and EcoSpold2).

6.4.1. Integrating MIPS and Carbon footprint into LCA

A novel LCA method was theoretically developed in the myEcoCost project (myEcoCost n.d.), which is a new LCA method measuring all material flows and substances. The process for defining and installing this new LCA method in LCA software will be described in the following sections.

RACER is a qualitative based assessment approach that is used to select feasible LCA method (Lutter & Giljum 2008), which is deeply discussed in Chapter 2. In the myEcoCost project, RACER approach was used to evaluate the existing LCA methods, and the Material Footprint and Carbon Footprint were selected as feasible LCA methods for the project objectives. Therefore, this new LCA method is an integration method consisted by Material Footprint as core indicator and Carbon Footprint as the satellite indicator.

The Material Footprint as an input oriented indicator is part of the MIPS-concept (material input per service unit) developed by the Wuppertal Institute for Climate, Environment and Energy (Saurat & Ritthoff 2013) . The calculation of MIPS is divided into the abiotic material, biotic material (Schmidt-Bleek & Bierter 1998). All emissions and related impacts result from the extraction of natural resources it is assumed that a reduction of input leads to a decrease of emissions and environmental impacts. Hence, MIPS is able to measure the overall raw material consumption of a certain product or service throughout its entire lifecycle.

The Carbon Footprint is a derivative of the ecological footprint invented in 1991 by the Canadian ecologists William Rees and Mathis Wackernagel at the University of British Columbia (Wackernagel & Rees 1998). Carbon Footprint is the overall amount of carbon dioxide and other greenhouse gas (GHG) emissions (e.g. methane, laughing gas, etc.) associated with a product.

The Carbon Footprint Methodology is based on the LCA standard ISO 14067. For the calculation of the Carbon Footprint Global Warming Potential (GWP) factors defined by the Intergovernmental Panel on Climate Change (IPCC) will be used in this new LCA method. The GWP reflects the relative effect of a greenhouse gas focussed on climate change about a fixed period. For the myEcoCost method, the Carbon Footprint is calculated considering the overall GWP as defined in the IPCC 2007 model for a time period of 100 years.

Therefore, this new LCA method examines three environmental impact categories including material footprint abiotic, material footprint biotic, and carbon footprint. For the abiotic and biotic categories of the Material Footprint, corresponding substances and factors (see Figure 6.14) are provided by Wuppertal Institute (Wuppertal Institut n.d.), which is the myEcoCost project consortium member, and the research institution that developed this method. Moreover, for the Carbon Footprint, substances, factors, units (see Figure 6.15) are extracted from the IPCC 2007 methodology (Hischier et al. 2010). In order to define this new LCA method in LCA software, the substances, within these environmental impacts are needed to input into LCA software, along with their evaluation factors and units.

Figure 6.14. Abiotic and biotic substances, factors and units for Material Footprint

Elementary flows	Category	Subcategory	Unit elementary flow	abiotic	biotic	unit
Peat, in ground	resource	in ground	kg	1.25		
Aluminium, 24% in bauxite, 11% in crude ore, in ground	resource	in ground	kg	8.542		
Anhydrite, in ground	resource	in ground	kg	1.072		
Barite, 15% in crude ore, in ground	resource	in ground	kg	10.667		
Basalt, in ground	resource	in ground	kg	1.01		
Borax, in ground	resource	in ground	kg	1.1		
Cadmium, 0.30% in sulfide, Cd 0.18%, Pb, Zn, Ag, In, in ground	resource	in ground	kg	1		
Calcite, in ground	resource	in ground	kg	1		
Carbon, in organic matter, in soil	resource	in ground	kg	1		
Cerium, 24% in bastnasite, 2.4% in crude ore, in ground	resource	in ground	kg	41.667		
Chromium, 25.5% in chromite, 11.6% in crude ore, in ground	resource	in ground	kg	18.879		
Chrysotile, in ground	resource	in ground	kg	1		
Cinnabar, in ground	resource	in ground	kg	1		
Clay, bentonite, in ground	resource	in ground	kg	1.24		
Clay, unspecified, in ground	resource	in ground	kg	2.304		
Coal, brown, in ground	resource	in ground	kg	4.2		
Coal, hard, unspecified, in ground	resource	in ground	kg	5.282		
Cobalt, in ground	resource	in ground	kg	0		
Colemanite, in ground	resource	in ground	kg	1		
Copper, 0.52% in sulfide, Cu 0.27% and Mo 8.2E-3% in crude ore, in ground	resource	in ground	kg	419.123		

Figure 6.15. Substances, factors and units for Carbon Footprint

Elementary flow	Category	Flow property	Unit	Factor
Carbon monoxide, fossil	air/high popul	Mass	kg/kg	1.5714
Carbon monoxide, fossil	air/low popula	Mass	kg/kg	1.5714
Carbon monoxide, fossil	air/low popula	Mass	kg/kg	1.5714
Carbon monoxide, fossil	air/lower strat	Mass	kg/kg	1.5714
Carbon monoxide, fossil	air/unspecifie	Mass	kg/kg	1.5714
Chloroform	air/high popul	Mass	kg/kg	30
Chloroform	air/low popula	Mass	kg/kg	30
Chloroform	air/low popula	Mass	kg/kg	30
Chloroform	air/lower strat	Mass	kg/kg	30
Chloroform	air/unspecifie	Mass	kg/kg	30
Dinitrogen monoxide	air/high popul	Mass	kg/kg	298
Dinitrogen monoxide	air/low popula	Mass	kg/kg	298
Dinitrogen monoxide	air/low popula	Mass	kg/kg	298
Dinitrogen monoxide	air/lower strat	Mass	kg/kg	298
Dinitrogen monoxide	air/unspecifie	Mass	kg/kg	298
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	air/high popul	Mass	kg/kg	1430
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	air/low popula	Mass	kg/kg	1430
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	air/low popula	Mass	kg/kg	1430

6.4.2. Applying the LCA method in openLCA

In this research, openLCA is employed to demonstrate the installation process. The installation in openLCA begins with creating a new impact assessment method called myEcoCost, by right clicking ‘Impact assessment methods’ and selecting ‘New LCIA method’ menu, as Figure 6.16 (left) shown. In the pop-up tab page, creating three new impact categories and defining units by clicking the ‘+’ button, which includes carbon footprint, material footprint abiotic, material footprint biotic, as Figure 6.16 (right) shown. Last, clicking the ‘impact factors’ tab to input the corresponding substances information, including factors, units, flow property, etc. as shown in Figure 6.17.

Figure 6.16. Creating a LCA method and defining the impact categories in openLCA

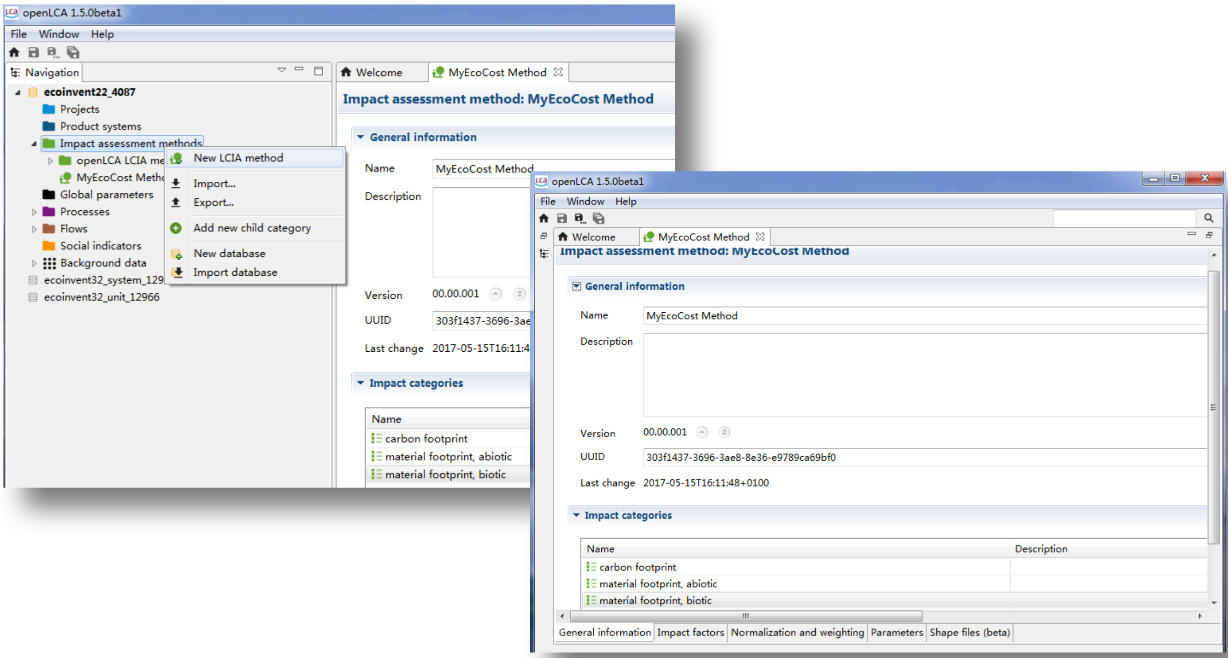
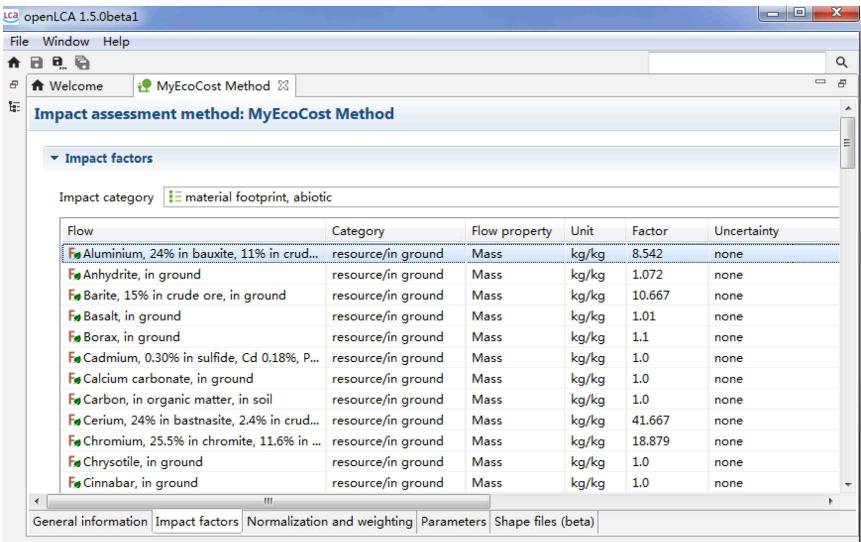
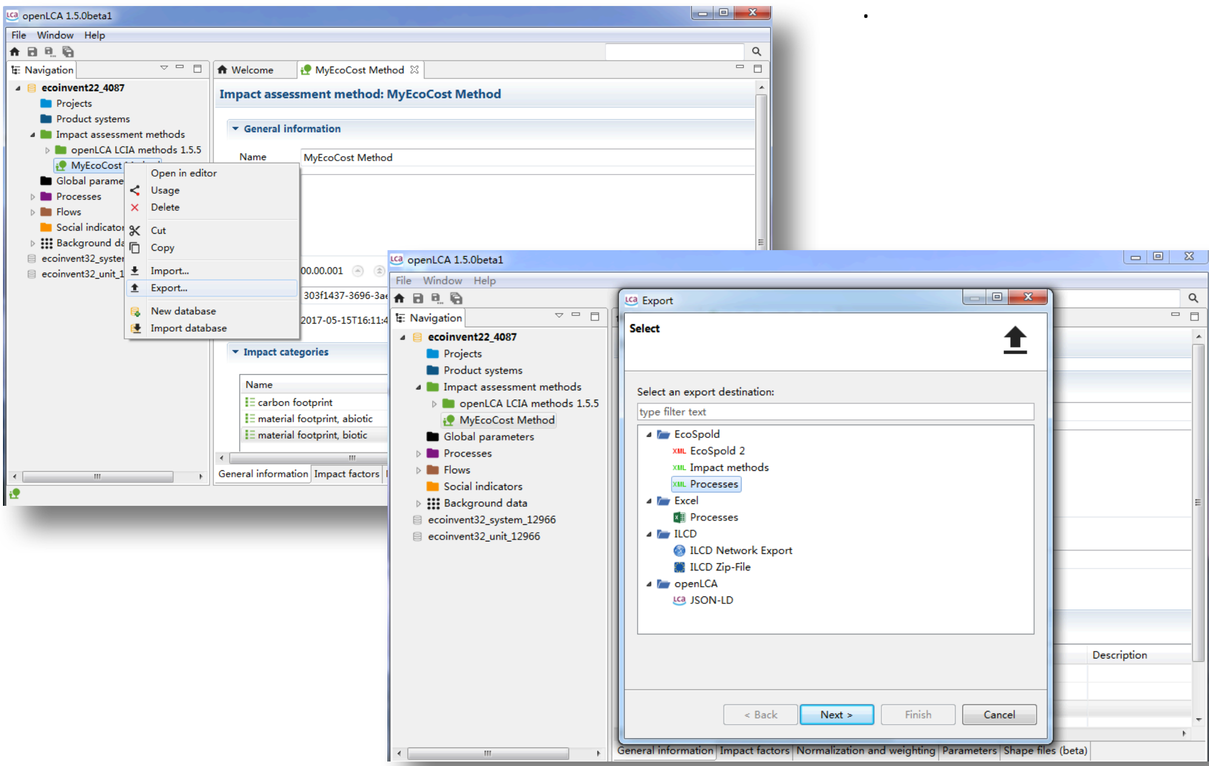


Figure 6.17. Substances, factors, units, properties for each environmental impact categories



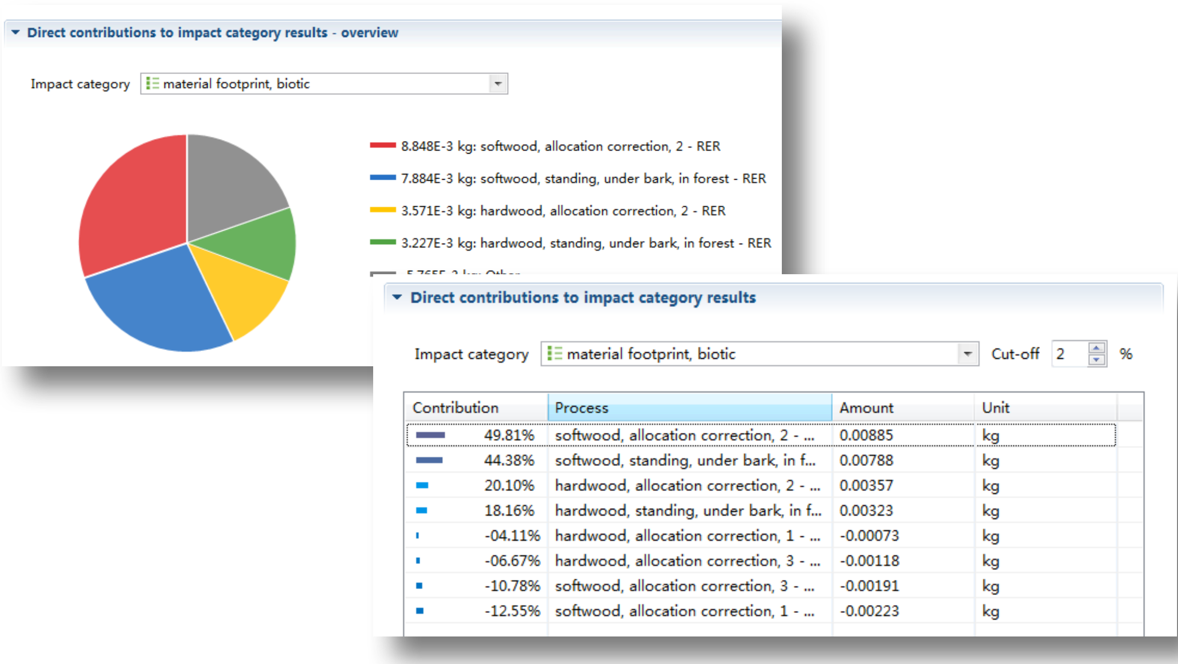
The installed LCA method in openLCA can also be exported for other users to use, by right clicking the 'MyEcoCost Method' and selecting 'export', as shown in Figure 6.18 (left). After left clicking 'export' button, an export format selection dialogue appears, as shown in Figure 6.18 (right). The supported export formats include EcoSpold 2, XML, ILCD, and JSON. Users can select the proper format according to their demands, and import the exported LCA method file into LCA software tools to implement calculations with the myEcoCost method.

Figure 6.18. Exporting the myEcoCost method in openLCA



In order to validate the performance of installed LCA method file, a process (i.e. 'glass fibre, at plant') from ecoinvent v2.2 is evaluated with the myEcoCost method in openLCA. The evaluation results are presented in Figure 6.19. Wiesen et al. pointed out that characterisation factors are not suitable to fully consider in 'biotic material footprint', as elementary flows for biomass other than wood are missing in ecoinvent and other LCA databases (Wiesen et al. 2014). In order to pursuit a more accurate analysis regarding this category, it would be necessary to add new elementary flows for biomass to LCA databases used by the software. Hence, for the specific case of products containing biomass materials, the myEcoCost methodology leads to an underestimation of the biotic resources and can only be used for a rough estimation of the biotic Material Footprint. For all other kind of products, the myEcoCost methodology works properly.

Figure 6.19. Calculations results with myEcoCost method in openLCA



6.5. Summary

In order to serve LCI database into web-based applications, the ecoinvent v2.2 database is applied to convert into SQL format, which is a key novelty of this chapter as there is no study introducing the methods and techniques to process EcoSpold files. A framework for implementation of the conversion process is developed, which involves the EcoSpold files parsing and extracting, and storing in a CSV file. xml.sax library was used to implement the automated EcoSpold file search, which is invoked by a Python script. The extracted LCI datasets were successfully imported into the SQL database management software, which demonstrates the conversion method and used technologies are useful for processing EcoSpold files.

As a novel feature in this research, a Java based GUI application implementing LCI data bridging function is also developed and introduced. The process of generating EcoSpold1 file is carried out by first acquiring the LCI data records. Then, other missing data in the database are supplied via user input in the developed GUI. By merging this two stream of data inputs, the EcoSpold1 is generated and ready for importing into openLCA. As a result, the aggregated LCI data is transferred into LCA tools, in order to conduct life cycle analysis of the corresponding products.

A new LCA method is defined and installed in the LCA software, openLCA, which consists of three impact categories: material footprint abiotic, material footprint biotic and carbon footprint. The defined LCA method is also exportable, with four type format files support, The generated LCA method file containing can be downloaded from Sustainable Production Support Toolbox, which would be beneficial for users to conduct LCA calculations with this novel method in their computers.

Chapter 7: Development of a web-based product environmental performance evaluation system

7.1. Introduction

The findings of literature review show that, the main LCA software (e.g. SimaPro and GaBi) is based on desktop-based software environment so that they are not able to perform flexible LCA services and LCI data sharing functions, which restrain the LCA performance for product environmental performance evaluation at the level of value chain. Although, there are a few web-based LCA application/software that can only offer basic LCA functions with limited databases and methodologies, For example, the web-based LCA software, Sustainable Minds, only provides TRACI methodology (Bare 2011) with pre-defined datasets that is a custom database, and are not allowed users to import other LCI databases. This type web-based LCA software/application is more suitable for users without much LCA knowledge or demanding quick and straightforward LCA results.

Within this context, this research project aims to develop a robust web-based product environmental performance evaluation system offering the same level functions as the desktop-based LCA software can provide, which generally includes LCI database import/export and modification, product lifecycle modelling, life cycle impact evaluation, and multiple analytical results presentation models, etc., which is a novel work in the LCA practical research fields. Moreover, according to the literature review findings, there is no an application performing the LCA services on the mobile platform. The benefits of implementing LCA functions in the mobile platform include aggregating accurate data reflecting the performance of product EOF, and promoting sustainable consumption behaviours for consumers. Therefore, an iOS-based mobile application has been designed and developed, which will be reported in the following sections.

7.2. The challenge of LCA calculation efficiency

7.2.1. LCA calculation

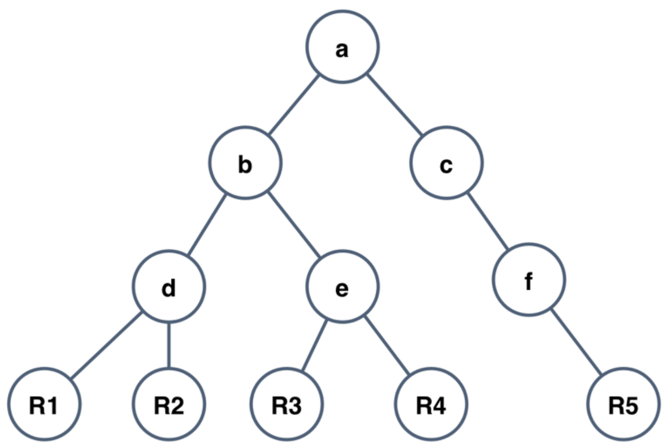
One of the key challenges involved the development is to improve the efficiency and speed for performing complicated calculations in the web environment. An open source High-Performance Calculation Library (HPCL) is applied to solve the linear algebra involved in the LCA calculation. Additionally, for the presence, there is no study explaining the logics behind the LCA calculation. The following section will start to describe it, and then to introduce the method of implementing the HPLC to improve the efficiency of LCA calculations in the web environment.

The key elements of each LCA-based calculation are the indexes (i.e. meanValue in the ecoinvent data format files) reflecting the performance of a type of production process or material in the particular environmental impact category, and the weighting parameters are used to concrete the finalised calculation results. The general rationale of the LCA mathematical calculation is to match and process these indexes and parameters with one unit values of each process or material involved with the product system. On the other hand, the LCI database characterises datasets by their various properties, such as resources (i.e. elementary flows in the ecoinvent data format files) and production process type.

Additionally, the modelling of product life cycle usually shows that one type of material/resource or manufacturing process involves in multiple product systems, for example, in the modelling of a shampoo product life cycle, the ‘mixing' is not only a production process for manufacturing the shampoo but also a manufacturing process for packaging materials, which is also a typical situation within a complex product system.

To improve the efficiency of calculation, it is required to facilitate the organisational structure between processes and resources within a product system. The relationship between processes and resources is described as a tree structure. For example, given a set of processes P {a, b, c, d, e, f} and a set of resources R {R1, R2, R3, R4, R5}, the organisation structure of them can be described as shown in Figure 7.1.

Figure 7.1. A tree structure describing the relationship between processes and resources

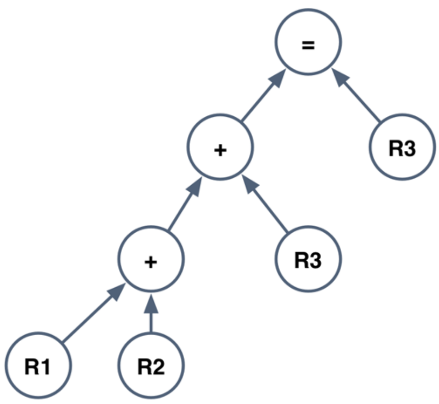


In Figure 7.1., each node of the tree represents a production process or a resource flow. A parent-child relation between two nodes represents a belong-to relationship between the elements on the nodes. All parent-child relations can be defined as a set of L {(a, b), (a, c), (b, d), (b, e), (c, f), (d, R1), (d, R2), (e, R3), (e, R4), (f, R5)}, which is a 2-place relation over $P \cup R$. Then the organizational structure tree is a pair (S, T), where S is the union of R and L ($R \cup L$), while T is a 2-place relation over S such that for each element a, a ∈ S, if a has a parent y, y ∈ S, then (y, a) ∈ T.

Based on these explanations and demonstrations, the organizational structure tree of the above example can be defined as: ({a,b,c,d,e,f,R1,R2,R3,R4,R5}, {(a, b), (a, c), (b, d), (b, e), (c, f), (d, R1), (d, R2), (e, R3), (e, R4), (f, R5)}).

For the demonstration purpose, Figure 7.1 only shows a 4-tier relationship between processes and resources among a life cycle of product system, however, in the real practices, a product life cycle is usually represented by a 20-tier relationship, which cause extreme burdens for the efficient calculations. In order to express this organizational structure with programming language, a simple tree structure is presented in Figure 7.2, the expressions of which is given as follows:

Figure 7.2. A tree structure showing the evaluation logics



Example: R3 = R1 + R2 + R3

Expression templates: “+” returns an expression => expression tree, for example:

A+B returns:

```
Sum<type_of_A, type_of_B> {
        const type_of_A &A;
        const type_of_B &B;
};
```

So the complete example:

```
        Assign<Matrix,
                Sum<Sum<Matrix, Matrix>, Matrix>>
```

In order to create a top-down evaluator:

```
        Evaluator<Sum<type_of_A, type_of_B> > {
          Evaluator<type_of_A> evalA(A);
          Evaluator<type_of_B> evalB(B);
          Scalar coefficient (I, j) {
                return evalA.coeff(i, j) + evalB.coeff(i, j);
          }
        };
```

Therefore, the assignment of produces are as follows:

```
        for (i=0; i<R3.size(); ++i)
                R3 [i] = R1[i] + R2[i] + R3[i]
```

Therefore, the process for searching the corresponding indexes in the LCI database, and matching these indexes with user defined values reflecting performance of resources and production processes are the core time-consuming activities for LCA calculations towards a complex product system. Because, for the LCI database, ecoinvent version 2 has 4087 data files (Hischier et al. 2010), and ecoinvent version 3 has 12,000 data files (ecoinvent n.d.) (see

Chapter 6 for development process). For assessing each process of a product system, the software calculation module has to search the whole data files in order to find the corresponding values.

7.2.2. Improvement of the LCA calculation efficiency

To implement this organisational matrix for LCA calculations, a High-Performance Calculation Library (HPCL), Eigen, is applied in this research to improve the effectiveness of this developed LCA calculation system. Eigen is a C++ template library for linear algebra: matrices, vectors, numerical solvers, and related algorithms (Eigen n.d.). This library is used for solving linear algebra problems in the LCA-based calculation, which is compatible with the development environment of the proposed system. Therefore, there are not extra efforts required for solving the problems that are usually caused by integrations. The benefits for choosing the Eigen library in this study include:

- Eigen is a free open source code library, which means users are free to download, use, modify and distribute it in the condition of complying with the terms of licence (Mozilla Public License Version 2.0).
- Eigen can be used on almost all servers that support Java, and the system database is a single database, e.g. MySQL, etc.

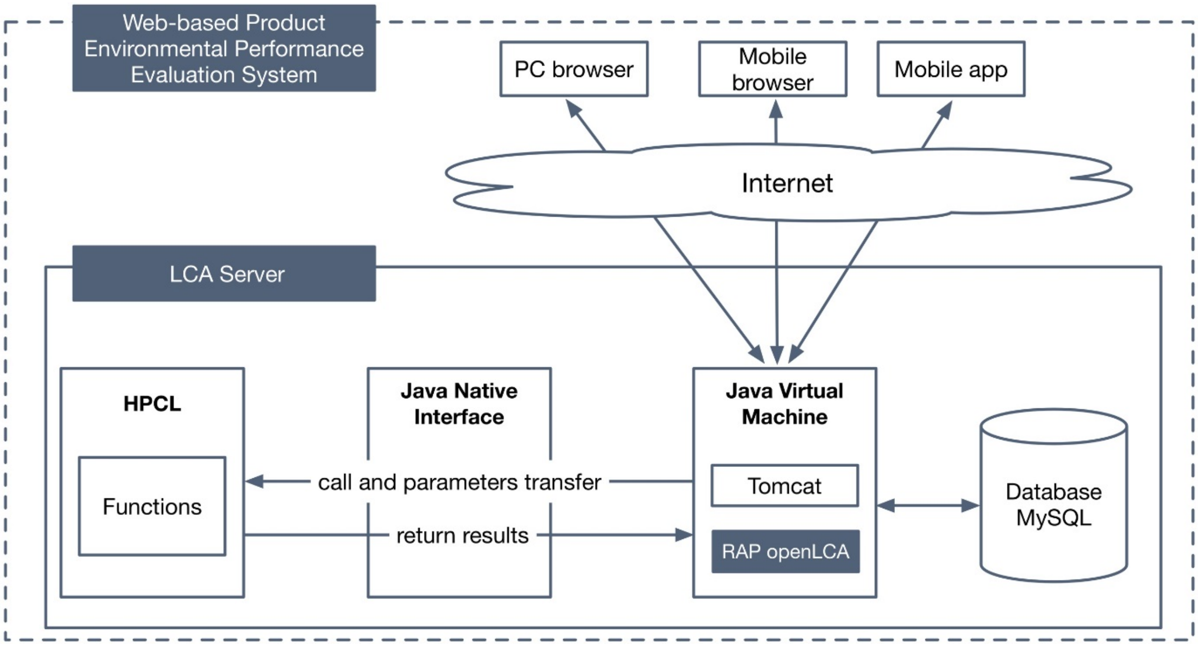
The method of developing the designed web-based product environmental system is to convert the desktop based openLCA into a web supported application with the great HPCL (i.e. Eigen). The reason for choosing openLCA is that it is an open source based Java application that runs on the Eclipse Rich Client Platform (RCP), which is a powerful desktop-based LCA application. This software is a plain Maven project that contains the core functionalities (e.g. the model, database access, calculations, and data exchange), which is licensed under the Mozilla Public License, v. 2.0.

7.3. Overview of the web-based product environmental performance evaluation system

Figure 7.3 presents the overview of the Web-based product environmental performance evaluation system, which consists of LCA server and client ends. The LCA server controls the four modules (HPCL, Java native interfaces, Java virtual machine, and associated database), and interacts with client ends (PCs and smartphones) over the Internet. As core of the Java virtual machine, openLCA provides with efficient real-time evaluation of product environmental performance, by enabling online LCA calculations and incorporating users' customised LCA methods and related database, which is a novel application.

In this system, Web Service is the key technology used to connect each component, where the openLCA package is located, and related services are available, to the Internet. The JNI (Java Native Interface) acts the role for bridging the HPCL and Web service. The operation procedure of JNI, HPLC and the Web server is illustrated in Figure 7.3. When a client requests a service, the client application sends a request and invoke a Java interface, which would create the request with these parameters. The server will analyse the received message to invoke the HPCL to implement a high-speed calculation and transfer back the calculation results into client applications and database.

Figure 7.3. Operation procedures for the web-based product environmental performance system



When the server receives the calculation command, the outer DII of HPCL is activated, and the DII will call Java program by JNI, which bridges the JVM (Java Virtual Machine) and the HPCL, as it performs high efficient communication between Java and C++ programme. The main invoked interface of openLCA is IMatrix, IMatrixFactory, and ISolver for solving linear algebra problems.

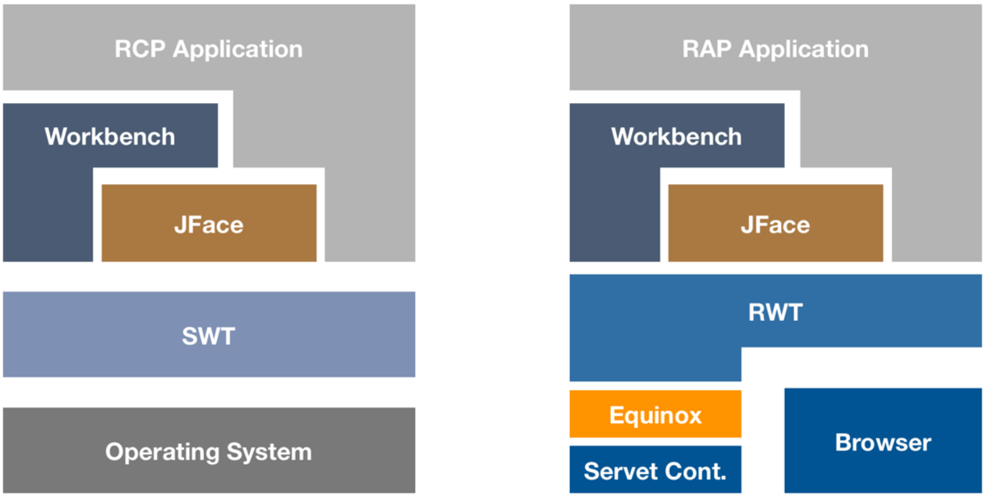
The openLCA is installed in Tomcat that belongs to Middleware. It plays the role to verify and transfer SOAP messages. The service provider needs to register their services to the service registry so that the information could be found by other requesters via the Internet. Then the service registry directs the service requester to find the right location of service. After that, service requester and service provider are bound to each other and ready to correspondence. The parameters captured by the program in the client are first packed in XML format. This is then ready to be transferred to communication message so that the service provider could receive and analyse it.

The consumer client application must be available for different types of devices and operating environments and in the web system, the consumer is presumed to have access to a desktop computer, a smartphone or a tablet. Each one of these different deployment modes presents a separate setup of challenges and limitations that have to be taken into account to allow the consumer to access the web-based product environmental performance evaluation system properly.

7.4. The server development

As openLCA is an Eclipse RCP based software, which means the toolbox used to develop this software is based Standard Widget Toolkit (SWT). RCP based application is only developed for the desktop operating environment. In order to convert it to a web-based application, Eclipse Remote Application Platform (RAP) is applied in this study, which is a framework for modular, web-based business applications in Eclipse. Additionally, user interfaces can be developed entirely in Java using a widget toolkit with SWT API, JFace and data binding.

Figure 7.4. Architecture differences for RAP and RCP application platform



The main differences between RAP and RCP regarding architecture are depicted in Figure 7.4. RAP is based Equinox, which is an implementation of the OSGi core framework specification, a set of bundles that implement various optional OSGi services and other infrastructure for running OSGi-based systems. This means RAP is suitable for solving issues related to session scopes, which is also the main difference with RCP application. For example, in RCP for users can get access the one and only UI representation instance from every part of the code since application scope and session scope is implicitly the same. Furthermore, RAP application is usually a multi-user environment (i.e. multiple sessions at a time), but there is only one application wide equinox instance running which is shared between those sessions (application scope). It is a complicated task for converting openLCA into a RAP based application, as each session has its workbench instance since the state of the UIs differs between sessions.

RAP is accessible for developing rich client applications and web applications from a single code base. Additionally, the existing RCP development skill and code base for web-based RAP applications are reusable, in the case of transferring openLCA into a web application, there are approximately 70%-80% of existing RCP code can be reused in the RAP environment without changes.

Hence, to transfer openLCA into a web application mainly involves the development of the custom widgets of openLCA. The custom widgets of openLCA are composed of two parts that are synchronised via the protocol: the server part that serves as a programming interface and the client part that is responsible for the representation. In this research, RAP version is employed, which can support direct access to the object on the opposite side via a RemoteObject. With this simple API, that corresponds directly to the operations of the RAP protocol, properties of the remote object can be changed, methods can be invoked, and event notifications can be received. This allows custom widgets to take synchronisation into their hands without having to register an adapter. Moreover, the web client offers a public JavaScript API for the first time, which also contains a RemoteObject for communication with the opposite side. The modification of custom openLCA widgets is not reported in this study, as it is the not this study objective.

As the existing Eclipse is not able to offer direct support for publishing a RAP application, a WAR file is needed to create with several Ant scripts and other resources, to package the developed files. Once the packaged WAR file created, it is required to move the WAR file to the web apps directory of the tomcat installation. The packaged RAP openLCA is installed on a computer with Intel i5 processor, and 8GB RAM. The operation environment is Ubuntu 14 with Tomcat 8.0, and MySQL 11.0.

The JNI is applied to implement the tasks of dynamic data processing and links with the HPCL and Web Service. The user operates the web-based product environmental performance evaluation system to input product LCI data and conduct calculations, with the aid of JNI and Web Service, to achieve the efficient and speed calculations. The JNI for invoking the HPCL is presented in Appendix 3.

7.5. Development of consumer mobile client

The mobile client is used by the consumer to fetch, evaluate and perform comparisons of product environmental impacts. The client also supports the consumer in their initial simpler overview of their purchased product environmental performance. There is no a mobile client application offering the described functions and services based on the extensive investigation towards the existing LCA software tool, and an iOS environment based mobile application is developed and reported in the following sections, which is also an innovation for this study. The benefits of employing this mobile client application include help consumers to select the environmentally friendly products and develop sustainable consumption behaviours. The consumer client application system is mainly of four main components:

- the consumer registration services for managing the access to the system.
- the Invoice services which allows access to the product invoice managed within the overall system.
- the Consumer Account Service that manages an individual consumer’ purchased products’ environmental performance.
- the Consumer HMI Service which manages the access by the consumer of their devices to their data in the application environment.

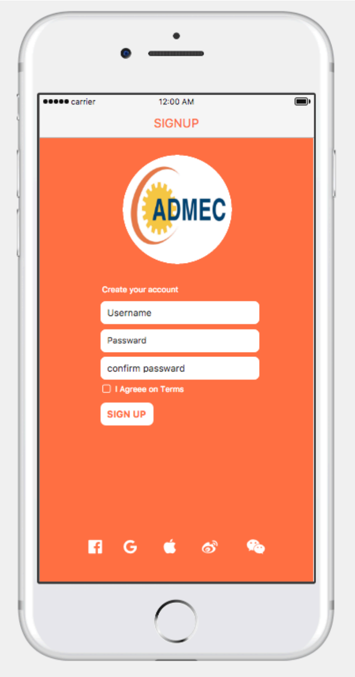
7.5.1. Consumer mobile client design

The Consumer mobile client manages the access by the consumer to their data using mobile devices and desktop computers as their primary tools. The developed mobile client is based on the iOS platform in this research.

The overall internal architecture of the systems in the Consumer HMI Service are based on individual modules activated and de-activated depending on the users' needs and accessing the data and information through standard information logistics objects shared by all modules and processes in the consumer tools system, which initiates the common steps of a LCA-based calculation that include the assessing the environmental performance of the various process and product categorizations.

Account management: As Figure 7.5 shown, the login screen allows the consumer to register when first connecting to the consumer client system. The consumer also can set preferences for their account and vital control information for statistics.

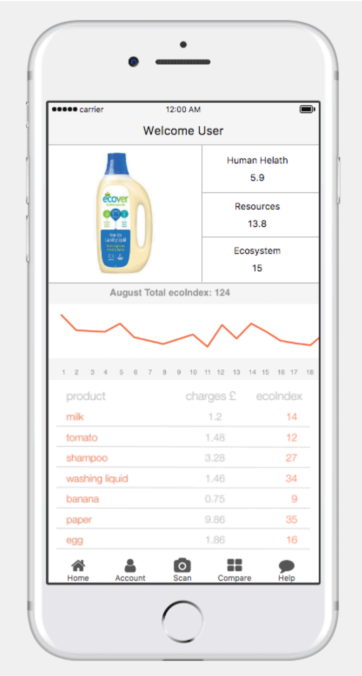
Figure 7.5. Consumer setting/login management screens

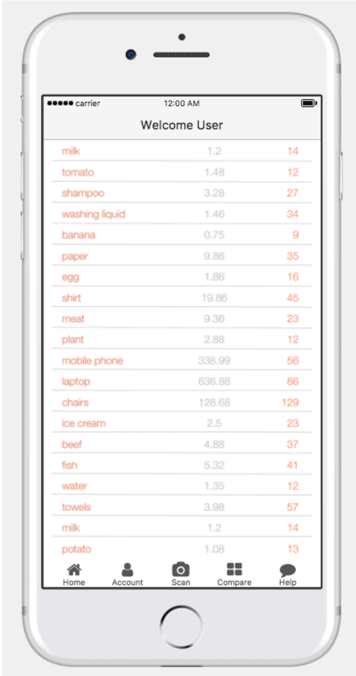


The user can at first login, register themselves either by their real name or by a selected user name and password. The user will be able to delete all their data except aggregate information that cannot be connected to an individual user of the system. The user shall be able to change their personal information and their password.

Invoice record management: As Figure 7.6 shown, the consumer can retrieve the recently purchased products environmental performance assessed by the default selected LCA-based methodologies, by quick scrolling the recorded product list. Once a product item is selected by users, the displaying window on the top of the screen will show the picture of the selected product, and the environmental impact indicators are presented to the right of the picture. Within the LCA service environment, ReCiPe is the default LCA methodology. Hence, the three environmental impact indicators are shown to the right of the displaying window. Moreover, there is an intuitive curve diagram demonstrating the overall purchased products environmental impact over a particular month, which would send the clear signal for users to pursuit sustainable consumptions.

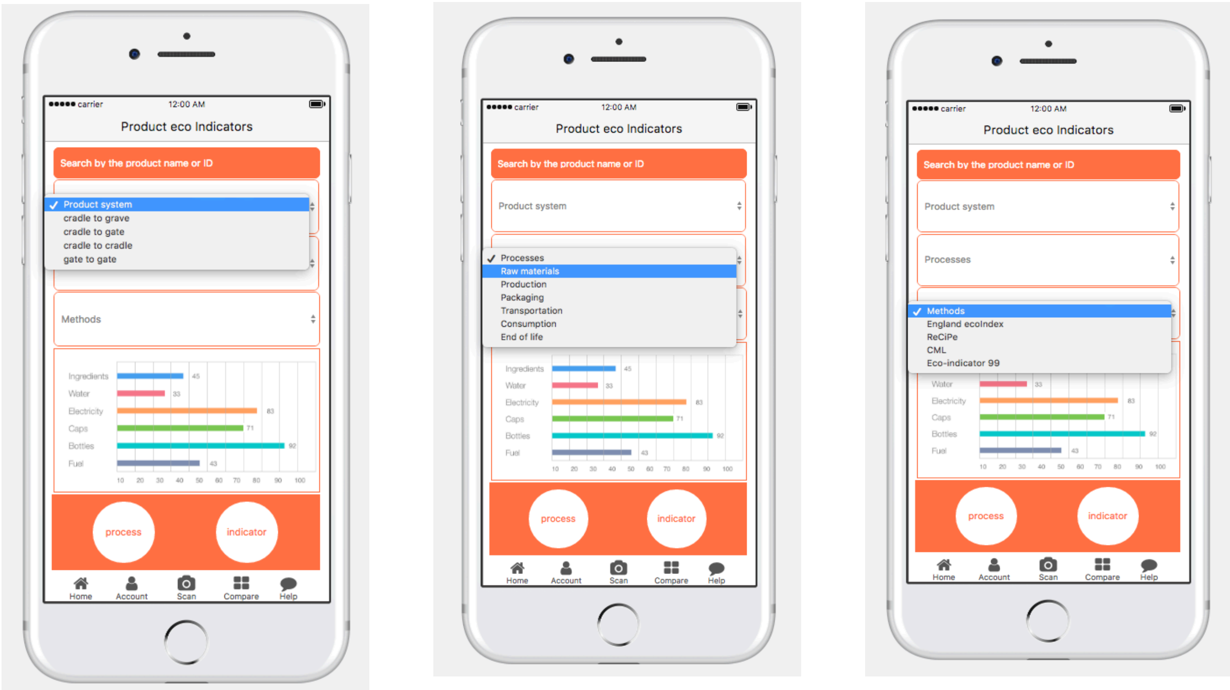
Figure 7.6. Consumer retrieve purchased product environmental performance screens





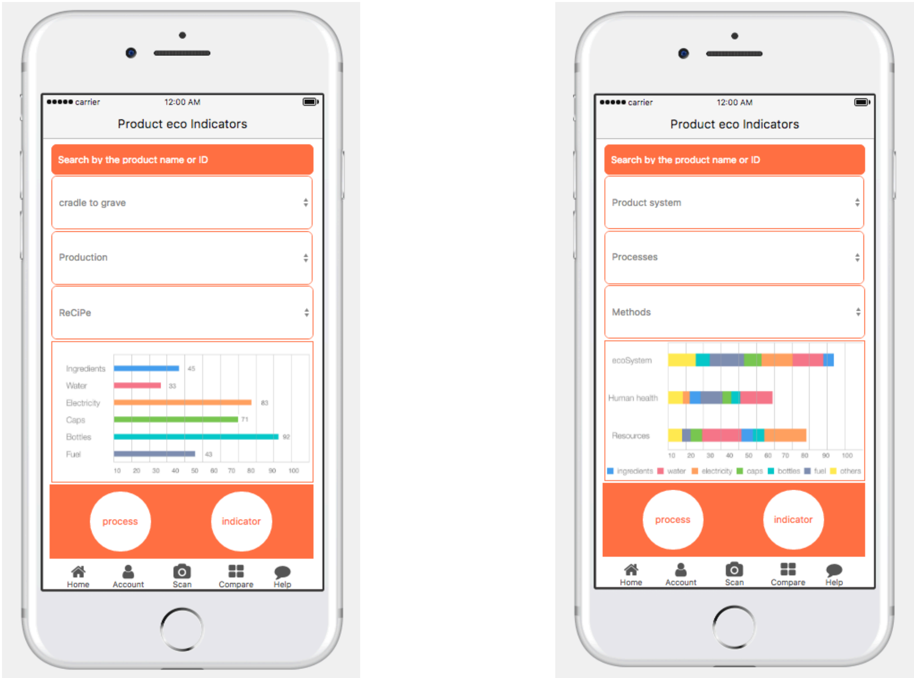
Calculation implementation and results presentation: The finalised results are presented on the homepage of this mobile application, once the user needs to check the life cycle environmental performance of the selected products, the 'calculation' page will appear by clicking the recorded product name. As Figure 7.7 shows, within this page, three properties are required to define by the user, which include the evaluation scope for the product system (see Figure 7.7 left diagram), evaluation process (see Figure 7.7 middle diagram), and evaluation method (see Figure 7.7 right diagram). Once the three properties are defined, the calculation will be automatically triggered, and the default presentation method is horizontal bar graph due to the limited screen space for the mobile application platform. Within the results displaying window, the environmental performance of the process or materials for the selected product are presented, which is easy to identify the root of pollution and emissions.

Figure 7.7. LCA calculation properties setting in consumer mobile client



As Figure7.8 shown, there are two different interfaces showing the calculation results for process flow and the selected methodology environmental impact (i.e. custom performance indicator). The two interfaces are switchable by clicking the two buttons (i.e. 'process' and 'indicator') in the screen. Within the 'process' page, x-axis lists the process or resource flows with high negative environmental impacts, and y-axis presents the value scale that is defined by the LCAI calculation API. Within the 'indicator' page, x-axis lists the indicators name that is defined by the selected calculation methodology, in this demonstration with ReCiPe methodology, hence, the three methodology endpoint indicators (i.e. ecoSystem, Human Health, and Resources) are listed in the x-axis line, and the value scale is shown in y-axis.

Figure 7.8. Calculation results presentation showing process performance (left) and indicator performance (right)



7.5.2. Development of consumer mobile client interfaces

Consumer Client application for the mobile device is developed using Xcode version 8.2 platform and the implementation is based on iOS 9 SDK and Swift programming language.

7.5.2.1. JSON-based data interchange for client application

The increasing trend for Web applications has fostered JavaScript Object Notation (JSON) as an alternative data interchange format to XML. JSON is based on a subset of the JavaScript programming language and can be natively parsed into JavaScript objects. In contrast, XML requires specific parsers for each XML-based language, which cause massive costs for Web applications. JSON consists of two structures: an object, a collection of key/value pairs, and an array, an ordered list of values. The values in an object or array can be other objects or arrays, strings, numbers, Boolean and null values. As objects and arrays map logically to standard programming language structures. Moreover, openLCA also support data transmission with JSON format, which will be compatible with the consumer client data communication. An example describing the 'Product System' data in the form of JSON format is presented in Figure 7.9.

Figure 7.9. An example showing 'Product System' JSON format

```
"@type": "ProductSystem",
"@id": "e673be33-b071-4ba2-9097-5b77a9c3ced2",
"name": "Ingot casting",
"description": "",
"version": "01.00.000",
"referenceProcess": {
  "@type": "Process",
  "@id": "55fd27b1-c73d-4a76-b560-cfc461e81efd",
  "name": "Ingot casting"
},
"referenceExchange": {
  "@type": "Exchange",
  "@id": "e4649009-ddb9-3c85-be99-1d635ffd3030"
},
"targetFlowProperty": {
  "@type": "FlowProperty",
  "@id": "93a60a56-a3c8-11da-a746-0800200b9a66",
  "name": "Mass"
},
```

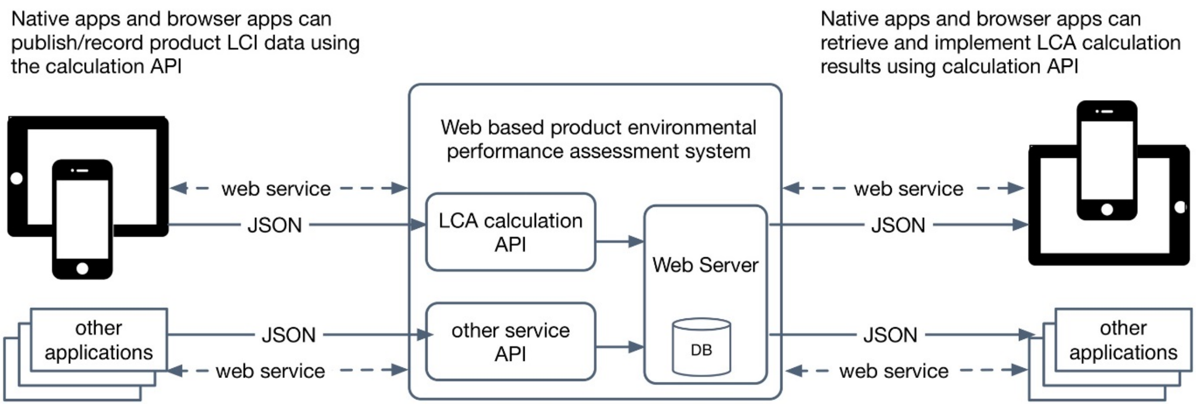
7.5.2.2. Data transfer model using Web Service

Web Service is also applied to the client as an application programming interface to allow the consumer to access the product environmental performance related data from the server and to send the commands to the server.

In the Web Service running environment, the control commands are processed as 'user requests, which are encoded with JSON rule for the communication with the server. When the user requests with control commands are sent to the server by calling Web Service via

HTTP, the server immediately passes the received requests to the corresponding API and subsequently transfers required/implemented data to the client in the form of JSON. JSON object is returned from a web service that can be converted it directly into native objects, such as NSDictionary, in the iOS application environment. These objects can be archived, and data elements are accessible by querying key-value pairs without having to implement delegate methods or iterate through the result data, which would improve the efficiency of consumer client based LCA calculations. The process flow of this mobile consumer client is depicted in Figure 7.10.

Figure 7.10. Process flow between the consumer client and the web server



7.5.2.3. Backend APIs for the interaction with RAP openLCA module

For the consumer client application, the involved calculations and processing activities are implemented by the backend API, offering the independent functionality for the frontend applications. For the developed web product environmental evaluation calculation module, there is a broad range of APIs implement various calculation functionality, for example, 'ImpactMethodExport' is used to export the EcoSpold file describing the property of LCA methodology, 'FlowPropertyExport' is used to export the all the involved flows for a product system. All these APIs are developed to support requests from multiple platforms, including enterprise level systems, for consumer client application, two APIs are mainly used to invoke the calculation results from server Database, which include ‘FlowExport’ and ‘RefDataExport’. ‘FlowExport’ can invoke the selected product primary datasets, the API of which is presented in Appendix 4. ‘RefDataExport’ can invoke the datasets reflecting properties of LCA calculation results, for example, the unit of calculation results, the indicators of LCIA methods. The API for ‘RefDataExport’ is presented in Appendix 5.

The backend API is enabled by Java Servlet technology to achieve web accessibility. JSON is selected for data communication formats, primarily with the aim to support the Web frontend. Upon receiving a request through HTTP, the backend parses incoming JSON to an appropriate object representing the request. Functionality classes are then invoked, delivering parameters extracted from the application message. Once the calculation is implemented, a suitable response object is built, serialised, and returned to the client as JSON format. The components to expose the API on the Web are decoupled from the classes used to perform data processing, enabling the API to be used as a Java library for integration with other applications.

7.6. Development of the database

The database maintains the connection to the database and manages all tables relevant for the systems and applications in the ICT platform. It also implements the filter functionality. Most entries in the database are directly stored but never deleted or changed. Products' processes and elementary flows once used for the calculation must be kept unchanged for auditing. Also, the general business and consumer data, LCI data, are also under management by this centralised database. The primary entities of the database domain are shown in Figure 7.11.

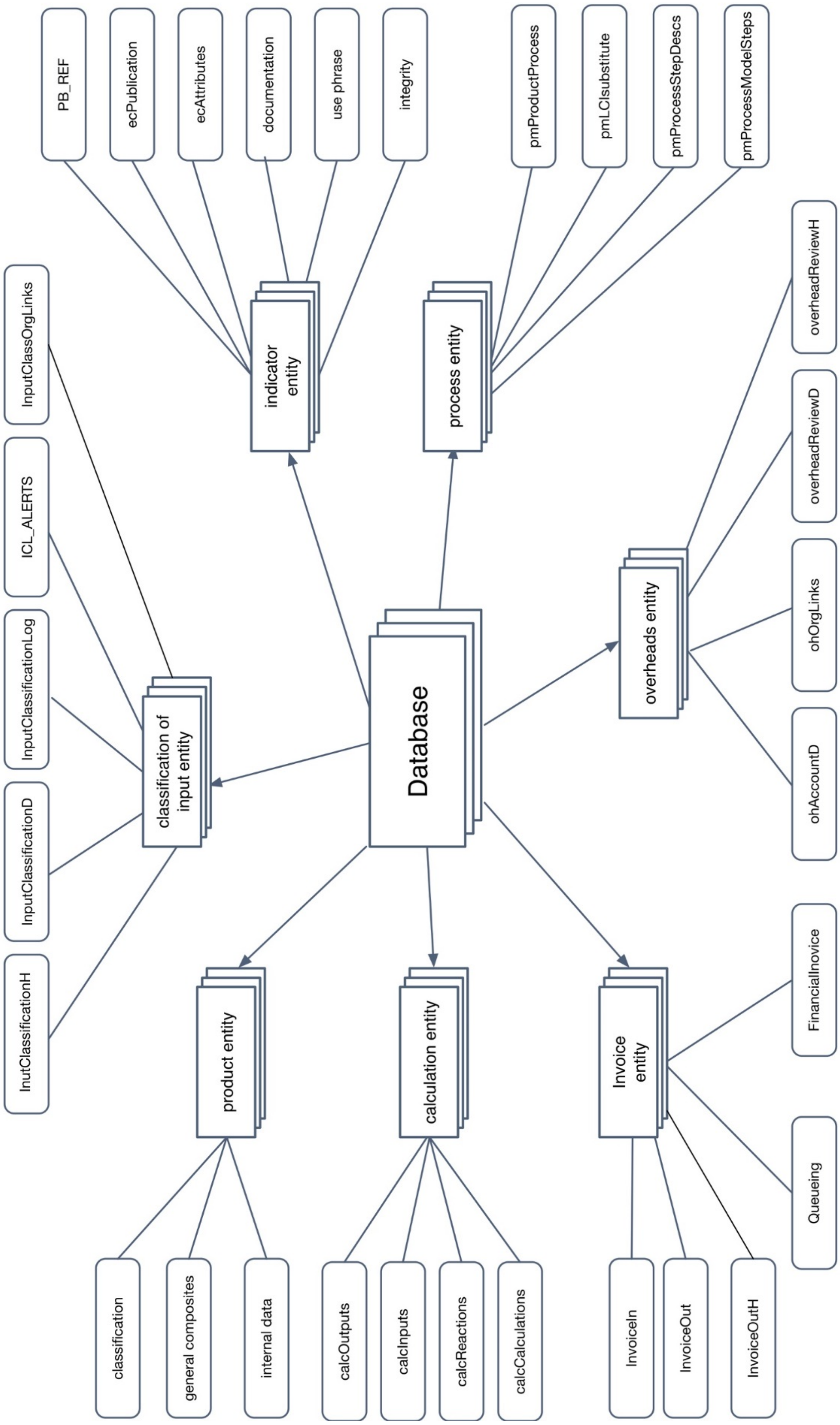
7.6.1. Designing entities for the database

Product entity: It is the system epicentre because the Product entity forms the basis of:

- The basis of inventory for use on a production line
- The basis of overheads
- Calculation of environmental impact within a company
- Finalised indicators being sent to consumers

The Product entity tables represent a product from the 'technosphere' – a product made by man, but the basis of all products made by man are 'products' that come from nature. The Classification table provides a means of classifying products for economy statistics. Each product can have its product code associated with. The Generic Composite table provides a means to describe a generic composite product, be it from nature or a descriptive from an LCI database.

Figure 7.11. High-level entities for the web-based product environmental performance evaluation system



Process model entity: A Process Model entity facilities a business to describe a process. The idea is to describe an entire manufacturing process, but this must be broad enough to consider an agricultural process or retail process. pmProcessModelSteps table gives the process a name and then describes the process as made up of any number of steps. Each step can have inputs, chemical reactions, calculations, and outputs assigned. Output can be either of:

- An emission back to nature (an elementary flow).
- By-product that is returned to inventory for use in a subsequent process.
- An input into the next step in the process.
- The final product that is sent to (sales) inventory.

To aid in the description of the process, each input/chemical reaction/calculation and output can have a brief comment associated with multiple tables, but a comprehensive description can also be assigned at any point in the process (pmProcessStepDesc). The core table in this entity is pmPorductProcess, which is a link file that associates a Process to a particular product. In many manufacturing situations, a Process will describe the mechanism to the manufacturer to a particular Product; there will be one product associated with a Process. But in a retail context, the Process will be the same Process to describe thousands of products. Therefore, there is the same sequence followed by thousands of products. In this way, the retailers can calculate the environmental impact of tens of thousands of products while maintaining several Process models only. pmLCIsubstitute table stores the substitute values from an LCI database. The use of substitute values would also be logged in the product integrity table.

Calculation entity: When the system is instructed to evaluate a product's environmental impact, the Process Model table will be read and used to process the calculation records of input products and any further modifications. When these calculation results are flowing into the calculator and reactions, and natural process are considered, a log of the calculation and movement of substances as it occurs will be used. At the end of the calculation, the chemical compounds and quantities will be determined from the records in these tables. There could be tens of thousands of records involved in these tables for a single environmental calculation.

Indicators entity: After the Process Model has been read and all the inputs, reactions, calculations and outputs have been taken into account, the result is a description of the final indicators of a product. The finalised indicators are expressed with the following tables.

The PB_REF n table refers to the precise calculation for a particular product. The manufacturing event to trigger is the production run on the factory floor. The system will send an instruction to 'evaluate for product X, making 2500 units'. This event and instructions is the foundation of this proposed system' dynamically calculated data premise, providing up-to-date values. The ecAttributes table stores the varieties of indicators, because an indicator is usually made up of subdivided resource indicators, these values are stored in this table.

It is massive consumption of the system resources that publishing a new evaluation indicator each time a figure is produced, so an average of evaluation indicators can be used for publication. This would result in less frequent publication and multiple advantages:

- Less network traffic due to fewer updated figures.
- Smoother indicators when comparisons the indicators of a single product over time, which is important for customer expectations.
- Possibly easier to manage as an internal corporate performance indicator.

Hence, ecPublication has been introduced. This table allows the distinction between an indicator calculation and the publication of an indicator for a product. This table allows a business to either publish indicators immediately upon calculation or defer publication with a view to averaging the outcomes over a period. The additional values contributing to the indictors are the Integrity (data quality markers), Use Phrase and Documentation.

Invoice entity: Another fundamental element in the distribution of indicator values is the eco-Invoice. The InvoiceIn and InvoiceOut tables store the Invoice for goods are purchased and come into an organisation, and goods are sold to customers, respectively. FinancialInvoice tables support the micro business who must send Invoice from manually generated commercial invoices.

To facilitate the efficiency of Invoice transmits, the Queueing table has been created. When the process to send an Invoice is initiated, it will look into the Queueing table instead of Invoice Out table to deliver the Invoice. By reading the queueEcoInvOut table under Queueing, the system will know which Invoices should be sent. When the service calls to transmit an Invoice is called and returns a complete result, the process will delete the record from the queueEcoInvOut table and update the InvoiceOutH record with a transmission timestamp, showing the job is completed. If the service call fails, the job remains in the queue.

Classification of inputs entity: When incoming Invoices arrive at a company, they need to be efficiently sent to the appropriate type of holding table. It has been determined that each purchase needs to be classified into one of the following:

- Inventory for use in manufacturing.
- An item whose evaluation indicators will be spread over a period of time.
- Overhead account.

To facilitate this classification, a set of rules are required to create for allocating inputs. InutClassificationH is header record that names the 'rule' and determines the action (inventory, capital or overhead). InputClassificationD is a series of detailed records associated to the rule. Each of these records represents a calculation that can be applied against the Invoice. If the calculation returns true, then the rule processing completes and the action in InutClassificationH is applied. There can be any number of these calculation records.

The InputClassificationLog file is there to record a summary of outcomes when the classification system is run. There may be 500 rules within the classification system; the classifier may run twice a day. This log file records how many Invoices were in the queue for classification, how many products were classified, how many remained in the queue. Items remaining in the queue indicate that a manual allocation may be required (for one-off entries) or the rules may need adjustment to classify a new product.

If any anomalous behaviour is detected while running the classification system, a note can be recorded in ICL_ALERTS, to be forwarded to an administrator to investigate. The InputClassOrgLinks allows a set of rules to be associated with any number of companies within the corporate group. Using a link table allows a single set of classification rules to be used across multiple companies, or for each company to have its set of rules or a combination of the two.

Overheads entity: The overheads are a critical facility within the ecoCalculator module. It is anticipated that the highest volume of product records will be processed through the overheads. Also, for service based companies, almost the entire system will be handled through overhead accounts. ohAccountH table supports the company to create the high-level name of each overhead account. ohAccountD table stores accumulation of company inputs, by using the internal columns to determine which period figures are assigned to. For example, electricity being attached to a particular product during production. ohOrgLinks table supports the company to set up any number of overhead accounts as it sees fit, and the internal columns are used to help allocate certain overheads to certain products. ohReviewProp table enables users to determine confirmed proportion of overheads to assign to a product; ohAllocationsLog table shows the basic operation information for each time an overhead is allocated to a product during its indicator calculation, which is essential for use in next periodic review.

The ERD (Entity Relationship Diagram) presenting all the database tables that have been developed and presented in Appendix 6. These database entities are developed in compliance with the requirements of the standard web product environmental performance evaluation environment. Moreover, the designed entities are applicable for any system that offers LCA-based services. Developing the SQL database for the web-based product environmental performance evaluation system is also an essential novelty of this study, as the extensive literature investigation shows that there is rare work discussing the development of database system relying on SQL format. Considering this database is of high working load, a full range of services have been developed to support the efficient operations, which is introduced in the following sections.

7.6.2. Main services for the data integration

7.6.2.1. Data service

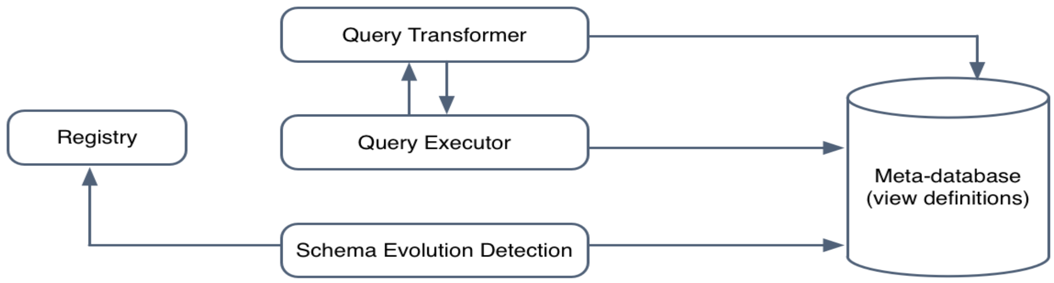
Each source database integrating into this system is managed by its provider through Data Service (DS) which receives queries and returns results. A DS exposes its reconciled schema and receives a standardised query that is on the reconciled schema, and then converts it into queries that are executable upon the schema of its underlying database. The query conversion is based on the specification of the mapping from the global schema to the local schema. This specification is named meta-data that is stored and maintained in the meta-database (MDB) at data source site by each data provider.

Each database provider needs to expose their database as a DS which can be accessed by data integrator service, and other external applications via a SOAP message. Four components are designed to implement the DS, and their workflow is depicted in Figure 7.12. Their functions are described as follows:

- Query Transformer: accepts the data queries sent from external applications and translate those queries into the query language that can be understood by this DS, and then is used to build the exporting views on the underlying source database.
- Query executor: decomposes the translated query based on the definitions of the exporting views and produce subqueries on the underlying local database schema.

- Schema evolution detection: is responsible for detecting any changes in the schema of the local database and examining whether the changes have affected the definitions of the exporting views.
- Meta-database: is the database where the local schema and the exporting views of the sources database are stored.

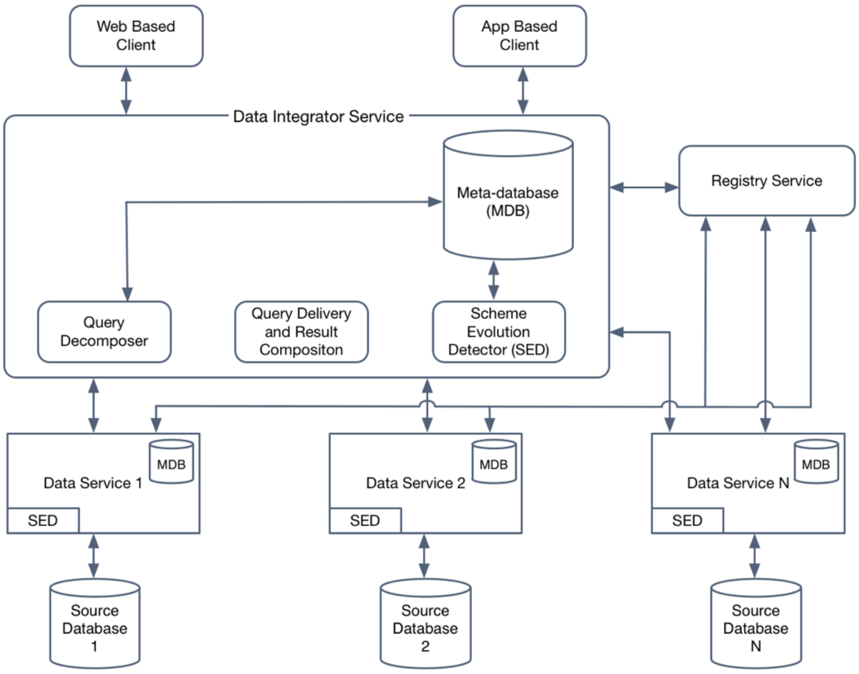
Figure 7.12. Main components of DS and their work flow



7.6.2.2. Data integration service

Data Integration Service (DIS) incorporates with DS, and the primary functions include: receiving a query from a user, and dynamically finding the source databases that provide data for this query; decomposing the query into subqueries referring to each source database, and then delivering the subqueries to corresponding DS. The query decomposition is implemented according to the metadata stored in the MDB of a DIS. The results produced by the DS are delivered to the DIS which subsequently composes those results into a final one and provides it to the end user. The workflow for principal components in DS and DIS are presented in Figure 7.13.

Figure 7.13. Main services for the data integration architecture



As Figure 7.12 shown, there are four main components for a DIS, which functions are described as follows:

- Query Decomposer: decomposes the query into subqueries that are in terms of importing views which represent source databases based on view definitions stored in the meta-database.
- Query Delivery and Result Composition: divides the subqueries into smaller pieces each of which is relevant to a single source database. It then sends those queries to correspond DSs that will return the results back to DIS.
- Meta-database: is a database for metadata of global schema and importing views of each source database. This is the major component in this database architecture as the main data processing in these systems are based on the information in the meta-database.
- Schema Evolution Detection: is invoked by the DS where changes in the local database schema occur. It is developed to monitor which importing views of the DS are affected by the changes, and to modify the affected views.

It is needed to note that there is only one DIS in Figure 7.20, more DIS are developed in the architecture performing the same function in order to enhance the performance of this architecture.

7.6.2.3. Registry service

Within this system, RS is a central module to enable dynamic service discovery. Both DS and DIS are published into a RS for other systems or services to discover the access. A RS is based on UDDI that contains only the information such as the time and the methods of a service. In this study, the registry service is designed to record basic information about all the DIS. The schema evolution detection of a DS can find all the DIS in the registry service. This method considerably reduces the cost of maintenance caused by the database evolution. In summary, the proposed data integration architecture is more flexible and scalable than the traditional SOA as it exposes source databases as DS instead of building wrappers for each database. Furthermore, the proposed architecture easily handles the data evolution because there are no hard-coded queries and programs for schema reconciliation.

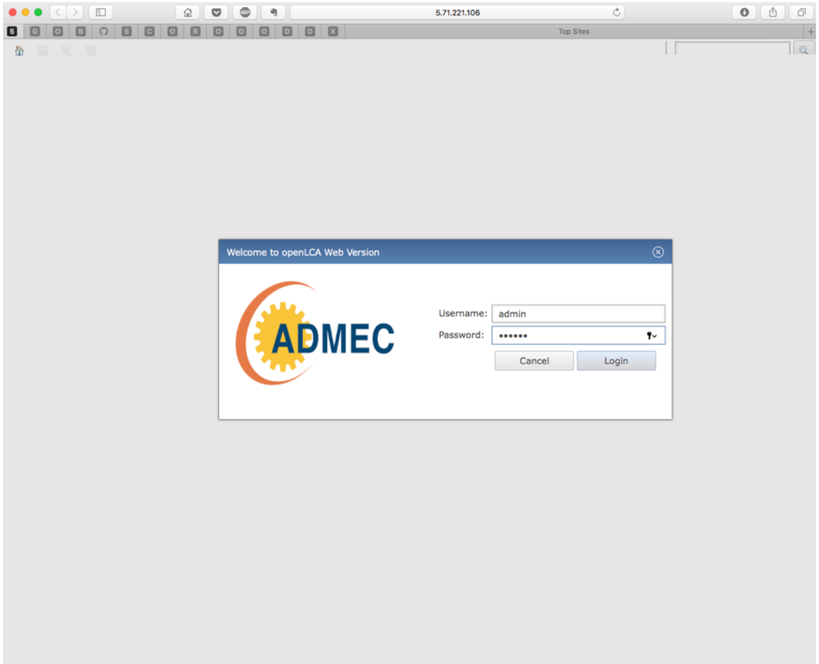
7.7. Validations for the web-based product environmental performance evaluation system

The validation is conducted with the following procedure:

- Login the web-based product environmental performance evaluation system.
- Using the stored LCI data of the shampoo product to create a product system.
- Selecting the life cycle impact evaluation methodologies to trigger a calculation.
- Comparing the indicator values of environmental impact with same data calculated in SimaPro, which is a powerful desktop-based LCA software.

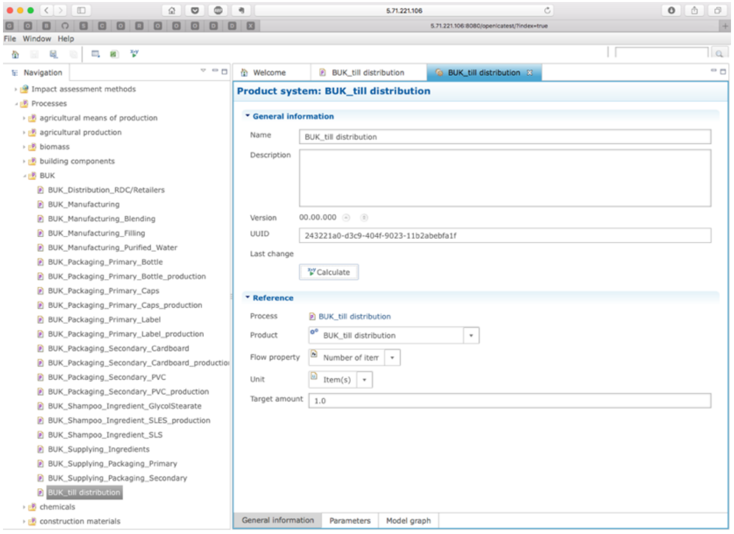
The rationale of this validation is to assure that the developed system can perform the designed functions and calculations results are compatible with other LCA software. The system is deployed in 5.71.221.106:8080/openlcatest/, and users are required to login in the system (see Figure 7.14).

Figure 7.14. Screenshot of the login page



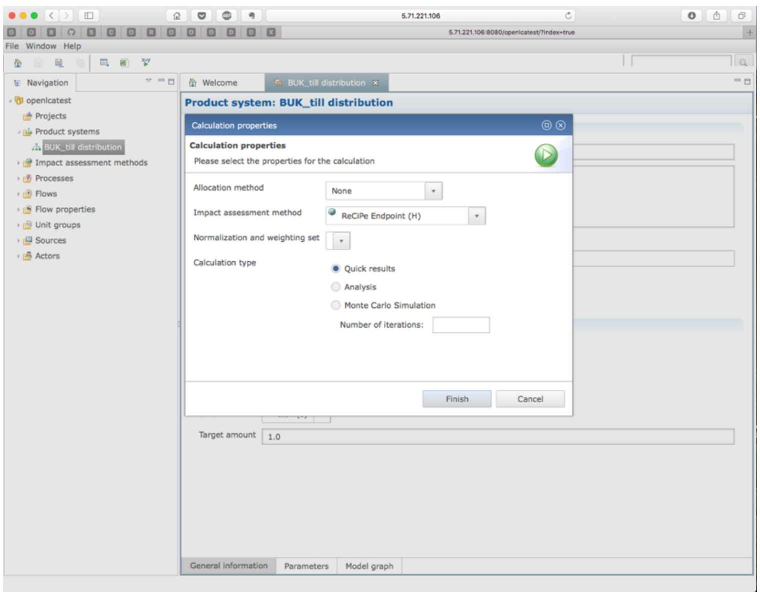
After logging into the system, the user can navigate the LCI data that this system contains, which include the data of ecoinvent 2.2, and other stored datasets. As Figure 7.15 shown, the data set describing the processes and resources of shampoo product life cycle have been stored in the system, and all of these files are placed in the BUK folder (see the left side of Figure 7.15).

Figure 7.15. Screenshot of the page showing creating shampoo product system



Cradle-to-gate scenario is employed in this validation, which means the LCA will only cover the following life cycles: materials, manufacturing, packaging. In order to create a shampoo product system for theses stages, it is only needed to open the 'BUK_till_distirbution' and click the button 'create a product system', then the product system operation interface will be automatically opened, as Figure 7.16 shown. Until this step, all the processes and resources belonged to the shampoo system are linked, and are ready to be assessed.

Figure 7.16. Screenshot of the page showing selecting LCA methodology



An evaluation will be implemented when users click the 'calculate' button in product system page (see Figure 7.16), and a 'Calculation Properties' dialogue will pop-up for users to select the feasible LCA methodologies (see Figure 7.16). The endpoint of the ReCiPe method is selected, and 'Quick results' model is also employed in this validation task, which means the calculation results will be presented with tables and pie charts. After clicking the 'Finish' button, a calculation is triggered, and result presentation pages will be shown in six different tabs, as illustrated in figure 7.17(a) and Figure 7.17(b). In the tab 'General information', two pie charts respectively show the shampoo product flow contributions and impact contributions in ReCiPe environmental impacts.

Figure 7.17(a). Screenshot of LCA calculation results with pie chart presentation

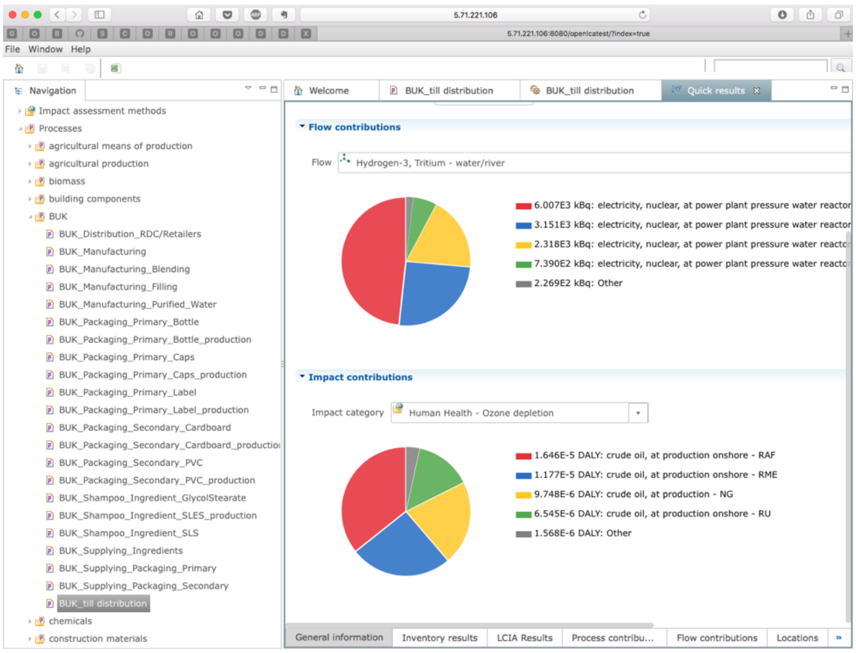
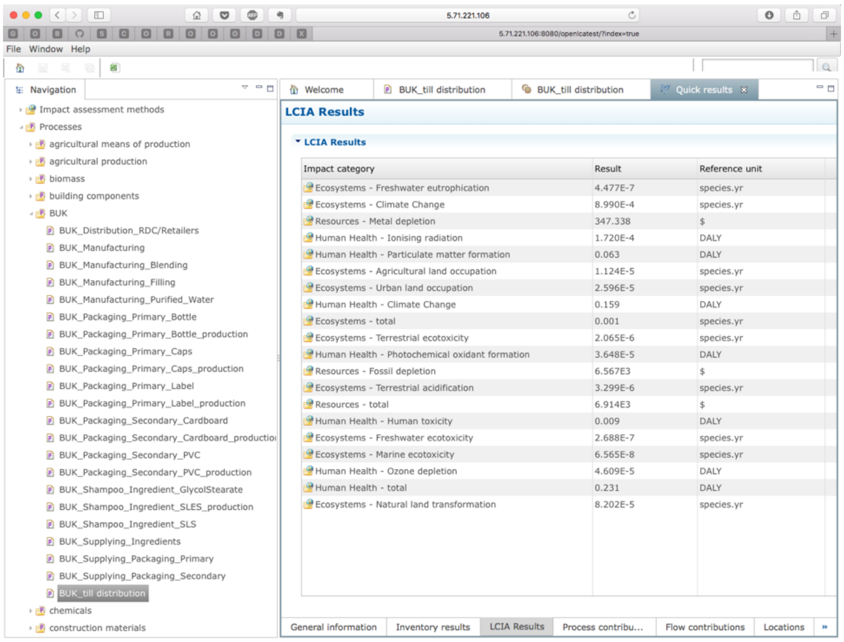


Figure 7.17(b). Screenshot of LCA calculation results with table presentation



The same LCI datasets were employed in this web-based product environmental performance evaluation system, and commercial desktop LCA software SimaPro, respectively, and ReCiPe methodology were selected to assess the shampoo product environmental performance, in order to compare the calculation results in two tools, and to validate the developed web-based LCA system is functional. Only the endpoint indicator results are reported in this section, as there are seventeen midpoint values within ReCiPe methodology, which is not necessary to present each of them. Furthermore, the endpoint values are the sum of the seventeen midpoint values, which means if there are vast differences between theses sub-categories, the endpoint values would be evidently different, either. The calculation results under three scenarios are shown in Table 7.1.

Table 7.1. Endpoint indicator value comparison in Cradle-to-Gate scenario

	Human health - total	***Ecosystems – total***	***Resource - total***
SimaPro	0.234 Pt	0.001 Pt	5943.219 Pt
Web-based system	0.231 Pt	0.001 Pt	6914.011 Pt

As Table 7.1 shown, the calculation results are relatively close. The identified factor causing this difference is that the ReCiPe methodology file version is different. The ReCiPe methodology version in SimaPro 8.1.1 is Endpoint (H) V1.12 / Europe ReCiPe H/A, which is a custom version offered by SimaPro vendor and are not allowed to modify it. The ReCiPe version used by the web-based system is ReCiPe version 1.11 (Endpoints), which is the only version offered by its official website. Furthermore, the LCA results are used to identify the process or materials with high environmental impacts or to compare the environmental performance of alternative materials or production processes. Therefore, it is not necessary to emphasise every unit result is exactly same with the results from that commercial and professional LCA software. The key point of this validation and comparison is to certify both groups of results lead to the same conclusions, for example, both group results show that the shampoo product causes the highest impacts in Resource within the cradle-to-distribution scenario.

7.8. Summary

This chapter offers detailed descriptions of the process and technologies of developing a web-based product environmental performance evaluation system. The developed system performs powerful and efficient web service based calculations, which is a novel web based system as the there is no existing application providing the powerful LCA functions regarding applying custom LCA method, implementing real-time online calculations, etc.

Detailed explanations for the logics of LCA calculations are discussed, as there is not study presenting the rationale of LCA calculations. In order to improve the efficiency of LCA-based calculation in the web environment, a High-Performance Calculation Library is applied, which is also the first study of applying the third-party calculation library in web-based LCA system.

The developed system also consists a iOS based mobile application for consumers, the main human machine interfaces are designed and illustrated in this chapter, which is a first LCA based application operating in the mobile platform. The developed application can help consumers conduct remote product environmental performance evaluation and comparison, as a result, helping them select low-environmental impact products and improve sustainable consumption behaviors.

A robust SQL-based database is developed, to support the web-based system that is proposed in this research, which offers an innovative entity design method for this database. Furthermore, DIS, DS and RS are developed to manage the data integration into the database. This developed system is validated by conducting a LCA towards a set of shampoo product data, and the calculations results are extremely close with results that are assessed by the SimaPro by applying the same datasets, which shows the developed calculation system is successful and powerful.

Chapter 8: LCA for the shampoo product

8.1. Introduction

The main objective of this chapter is the identification of the major aspects characterising the shampoo product life cycle and relevant environmental impacts. Thus, the analysis will highlight the indicator features that are part of the final model and that environmental performance is requested to account for.

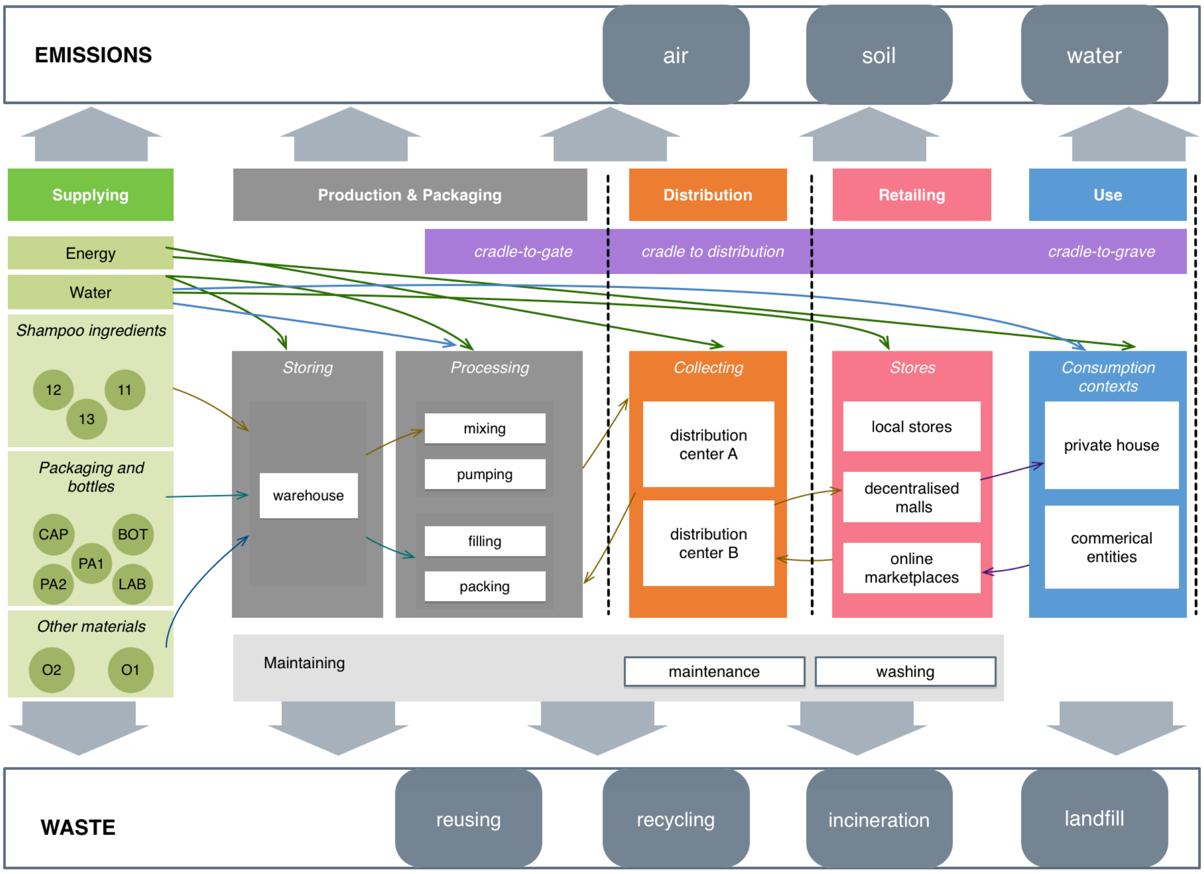
The shampoo product is manufactured in England, and according to the Confidentiality Agreement between Nottingham Trent University and the company, the company information and the product name are not allowed to reveal in this research, so the company name is aliased as BUK in this study.

The environmental impact assessment of the shampoo product is implemented by using the SimaPro (version 8.1.1) with the ecoinvent (version 3.2) database. ReCiPe method is adopted in the LCIA, and its version is Endpoint (H) V1.12 / Europe ReCiPe H/A (provided by SimaPro 8.1.1).

8.2. Boundaries of shampoo product life cycle

This section follows the general objectives of this study; hence, the whole product lifecycle has been considered for the environmental performance assessment. This implies the inclusion of Inputs and outputs throughout the whole production and consumption, from supplying to use and disposal. Moreover, a focused analysis on the manufacturing step has been added in order to provide primitive insights about the core activities. Figure 8.1 highlights the main activities and boundaries of life cycle for shampoo product that is analysed in this case study.

Figure 8.1. Mapping of the product life cycle boundaries and main activities



Therefore, the three scenarios that will be presented in this report are:

- Cradle-to-Gate: starting from the manufacturing and provision of shampoo blend ingredients at supplying stage till the gate of the manufacturing site.
- Cradle-to-Grave: from the supplying stage to the consumption and waste management.
- Cradle-to-Distribution: from the supplying stage to the distributions among warehouses and distribution centre.

The different nature of the above presented scenarios prompts the consideration of two different functional units. In the former scenario, Cradle-to-Gate, the analysis has been carried on considering the manufacturing of one batch of shampoo, equal to 4,500 litres of blended liquid in the vessel at production site. As a consequence, reference flows – as the number of ingredients, energy, and packaging among others – has been set as one batch as the functional unit.

Cradle-to-Grave, the boundaries have been extended to the final disposal after use, passing through the distribution process considering one hair-wash. Similarly, for above, the functional unit is a wasted hair, and the whole life-cycle of the product is account for in the measure it is needed accomplish the functional unit, i.e. the amount of resources is hence related to a single dosage of shampoo.

8.3. LCI of shampoo

The major source of data information is the manufacturer of the shampoo product, providing good quality data especially regarding:

- shampoo composition (excellent).
- ingredients data (average poor).
- suppliers distance (good).
- packaging composition (excellent).
- packaging production (good).
- shampoo manufacturing process (very good).
- storing and distribution (excellent).
- use (good).
- waste (poor to good, according to the previous steps sources).

Other complementary data used in this analysis is from ecoinvent 3.2 database.

In this section, the description of the major flows of materials, energy, and processes used in the three scenarios are reported and described in the following sections.

Raw materials

On the basis of data availability, the impacts from manufacturing and delivering of the following shampoo ingredients have been considered: water; sodium laureth sulphate; sodium chloride; glycerine.

These ingredients constitute the 96.9% of the total weight of the selected shampoo blend. The remaining 3.1% (inferior rate to the uncertainty margin in LCA studies at least 5-10%) is not expected to considerably influence the final results and especially the criteria for the findings to be delivered at the end of this study. The following raw materials have been neglected:

- Transport of ingredients from sourcing place to supplier (lacking of data or embedded in database datum)
- Packaging for delivering ingredients from suppliers to manufacturing site (lacking of data)

Packaging

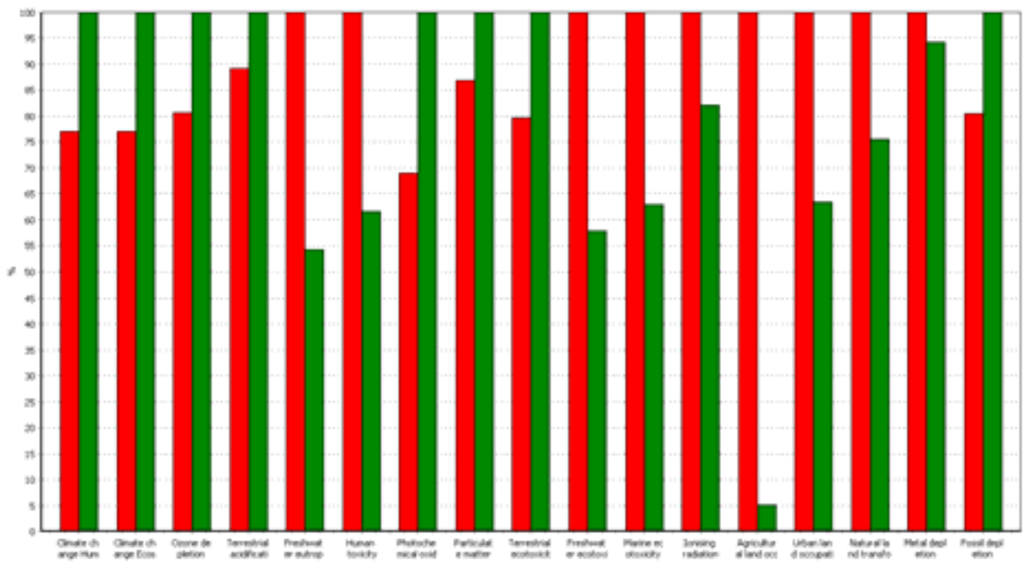
The packaging materials considered in this phrase include:

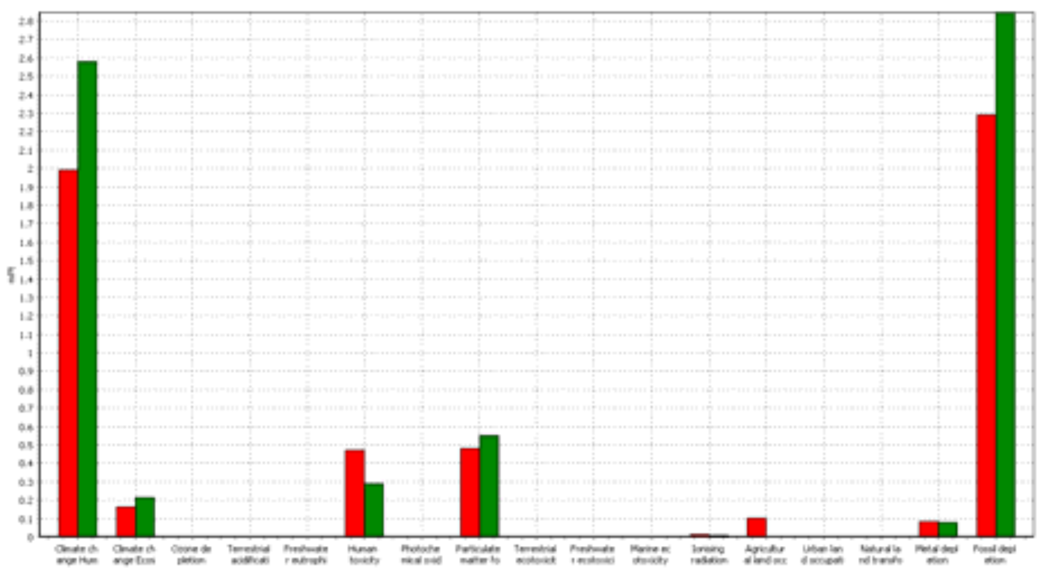
- Primary packaging: made of bottle, cap and label.
- Secondary packaging: made of cardboard box.
- Tertiary packaging: made of wood pallets and PVC film.

Bottles are made of PET, 30% of which from recycled pellets. The blowing processes for PET bottles has been based on primary data from the shampoo manufacturer. The impacts from this process has been compared with the impacts offered by ecoinvent database. As in

Figure 8.2, results are not particularly different, especially after weighting process, moreover, calculations by using datasets from ecoinvent are generally lower, which makes this choice conservative for the study.

Figure 8.2. Impacts for blowing process of PET bottles using ecoinvent database process (red bars) and data provided by the manufacturer (green bars), before (on the top) and after (on the bottom) of the characterization factors. Caps are made of Polypropylene and Label from self-adhesive silicone coated paper.





The following conditions for packaging have been assumed:

- Primary packaging production does not generate waste, that ought to be recycled internally.
- Silicone coated paper for label is equal to packaging paper process in the ecoinvent database: considering the extreme low amount of used material, significant changes are not expected.

Cardboard boxes can contain 40 bottles, and a pallet can hold 50 boxes, eventually wrapped with PVC film. After the delivery, cardboard boxes and PVC film are recycled, pallets are reused for 20 times, which is suggested by the manufacturer. The following conditions for packaging have been assumed:

- Secondary and tertiary packaging production does not generate waste, which will be possibly recycled.

Manufacturing

The manufacturing phrase mainly consists in the progressive adding and mixing of ingredients with slight variations of temperature during the process. The major inventory item in this phrase is the consumed energy.

The following conditions for manufacturing have been assumed:

- Absence of heat dispersion during the manufacturing process.
- 15 ml of blend waste during blending, mixing, and filling process (the manufacturer data).
- 255 ml of blend per each bottle, 5 ml of surplus respect to the amount in the label (the manufacturer data).

The following steps in manufacturing have been neglected:

- Process of water purification.
- Process for correcting the pH of the shampoo blend (only when necessary).
- Additional materials, e.g. lubricants.

- Washing after batches production.

Distribution

The study considered that items are firstly stored in the factory warehouse and then delivered to the distribution centres in England, before the final delivery to stores.

The following conditions for distributing have been assumed:

- Storing energy consumption in the manufacturer factory site and in distribution centres are equally allocated to the stored items by number – rather than weight or economic value.
- Distribution centres are located at an average distance of 226 km from factory site (average value suggested by the manufacturer).
- Stores are located at an average distance of 57 km from the distribution centre (average value suggested by the manufacturer).

The following steps in the manufacturing have been neglected:

- Energy consumption per item in stores.
- Waste in stores.

Use

The user phase accounts for both buying, and utilisation of a dosage of shampoo to wash a head. The following conditions for use phrase have been assumed:

- An average washing requires 10 ml of shampoo, and considering that 50% of people wash once per shower, 50% of people wash twice per shower. The final average value of 15 ml per wash is assumed (average value from the manufacturer).
- An average washing requires 7.5 litres of tap flowing water heated from 15 ºC to 35 ºC (Eskeland & Svanes 2006).

Waste scenario

The waste scenario is made of the following treatments, following the estimations by Defra in 2015 (DEFRA 2015) for packaging waste, as most of the steps in these scenarios generate:

- Recycling for 77.3% of cardboard and 21.9% of plastics amounts.
- The rest to landfill (83.1%) and incineration (16.9%).

Energy mix

The following consumed energy (associated to corresponding country mix) has been considered:

- Electricity for manufacturing in GB (Electricity, medium voltage, production GB, at grid/GB S).
- Electricity to heat water in the GB domestic (Electricity mix, AC, consumption mix, at consumer, < 1Kv GB S).

Transportation

The following average distances are provided by the shampoo manufacturer:

- From suppliers of ingredients (except water) and packaging (bottles, caps, labels, cardboard boxes) to manufacturing site.
- From manufacturing site to distribution centres and eventually to stores.

The following conditions for transportation have been assumed:

- Fully loaded and empty returns (conditions in ecoinvent data and close to average conditions in considered scenarios).

The following transportation have been neglected:

- From manufacturing site to warehouse in the same site (negligible for short distance)

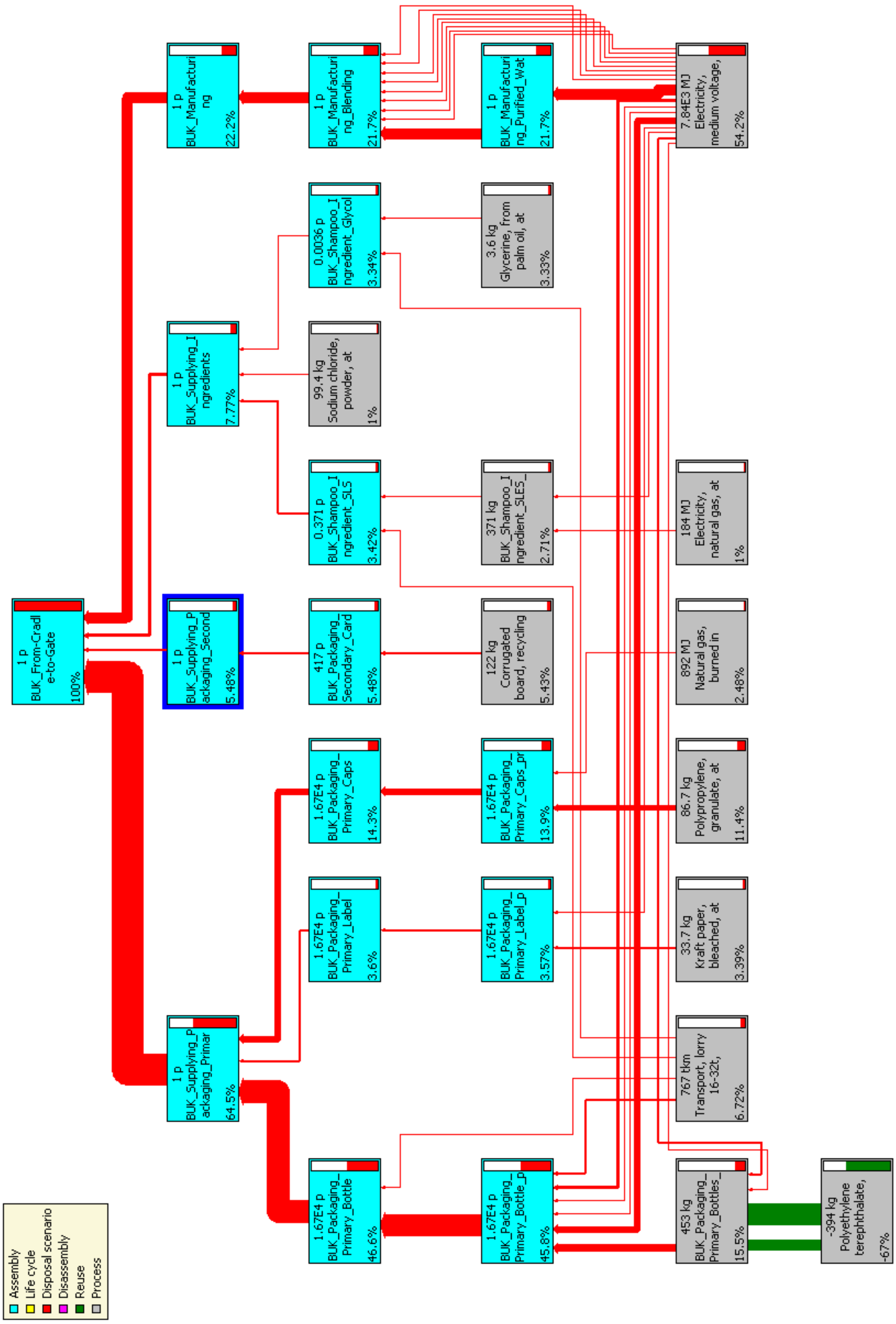
8.4. LCIA of shampoo product

8.4.1. Scenario 1: cradle-to-gate

As Figure 8.3 shows, most impacts are generated at this scenario by the supplying (i.e. production and transport) of primary packaging (64.5%), and by manufacturing process (22.2%).

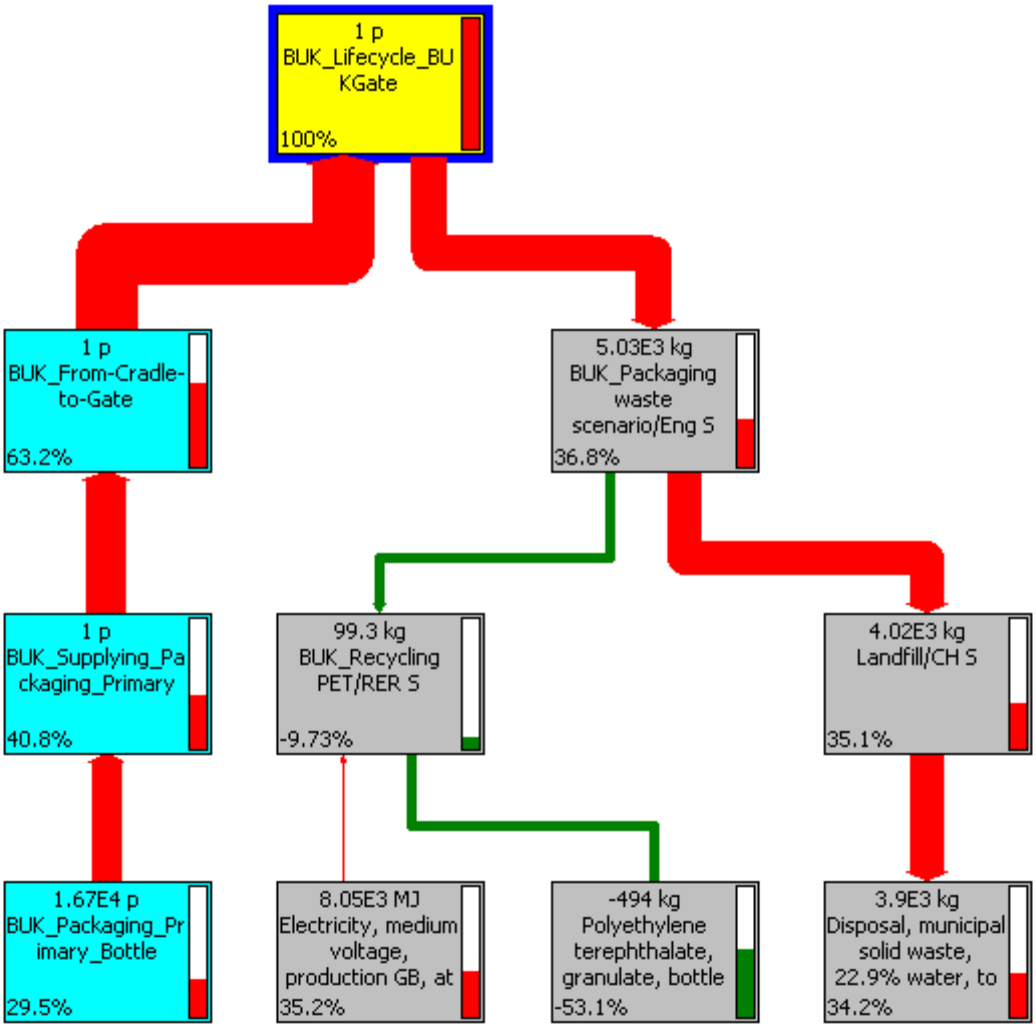
In the former case, PET bottle production causes the major impacts, while the manufacturing process is mainly influenced by the energy consumed for water provision. Both results could be expected considering the predominant presence of water in shampoo formulation, and simplicity of the manufacturing process in general. This datum could be significantly influenced once the energy consumed for water purification is considered in the calculation.

Figure 8.3. Flows of impacts in Cradle-to-Gate scenario with ReCiPe method (0.6% node cut-off)



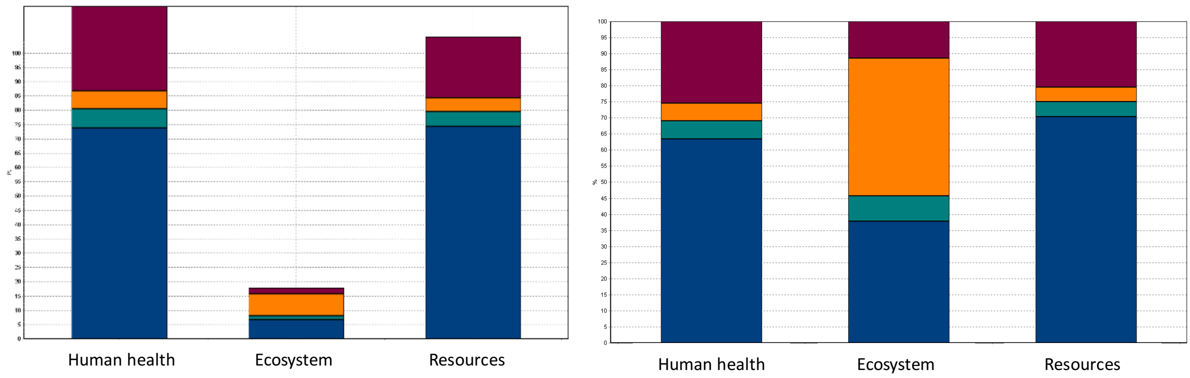
The inclusion of impacts from waste treatment evidently influences the results, as shown in Figure 8.4.

Figure 8.4. Flows of impacts in Cradle-to-Gate scenario (including waste scenario) with ReCiPe method (29% node cut-off)



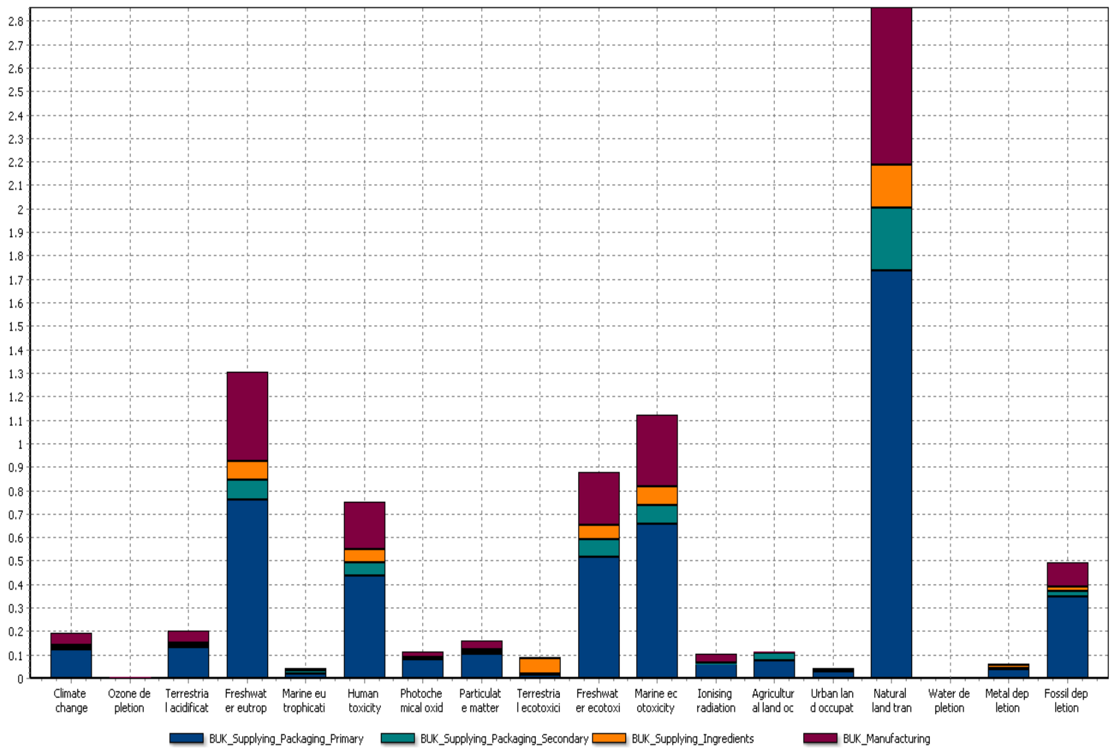
Damages generated by this scenario (disposal excluded) are shown in Figure 8.5, where the impact of Human Health (first column) and Resource (third column) are predominant after normalization and weighting processes.

Figure 8.5. Damages at Endpoint level, before (on the left) and after (on the right) normalization and weighting processes. Bars indicate the damages respectively: Human Health, Ecosystem, and Resource. Colour legend: blue for primary packaging production and delivery, green for secondary packaging production and delivery, orange for shampoo ingredients supplying, red for shampoo manufacturing.



Analyzing the same scenario on a Midpoint level (see Figure 8.6), a set of similar results in terms of impacts from the four main stages involved, where primary packaging supplying dominates (i.e. PET bottles production). After normalization, the following indicators emerges: Freshwater eutrophication, Human toxicity, Freshwater ecotoxicity, Marin ecotoxicity, and especially Natural land transformation. The supplying of ingredients dominates in Terrestrial ecotoxicity.

Figure 8.6. Damages at Midpoint level, after normalisation process. Colour legend: blue for primary packaging production delivery, green for secondary packaging production and delivery, orange for shampoo ingredients supply, red for shampoo manufacturing

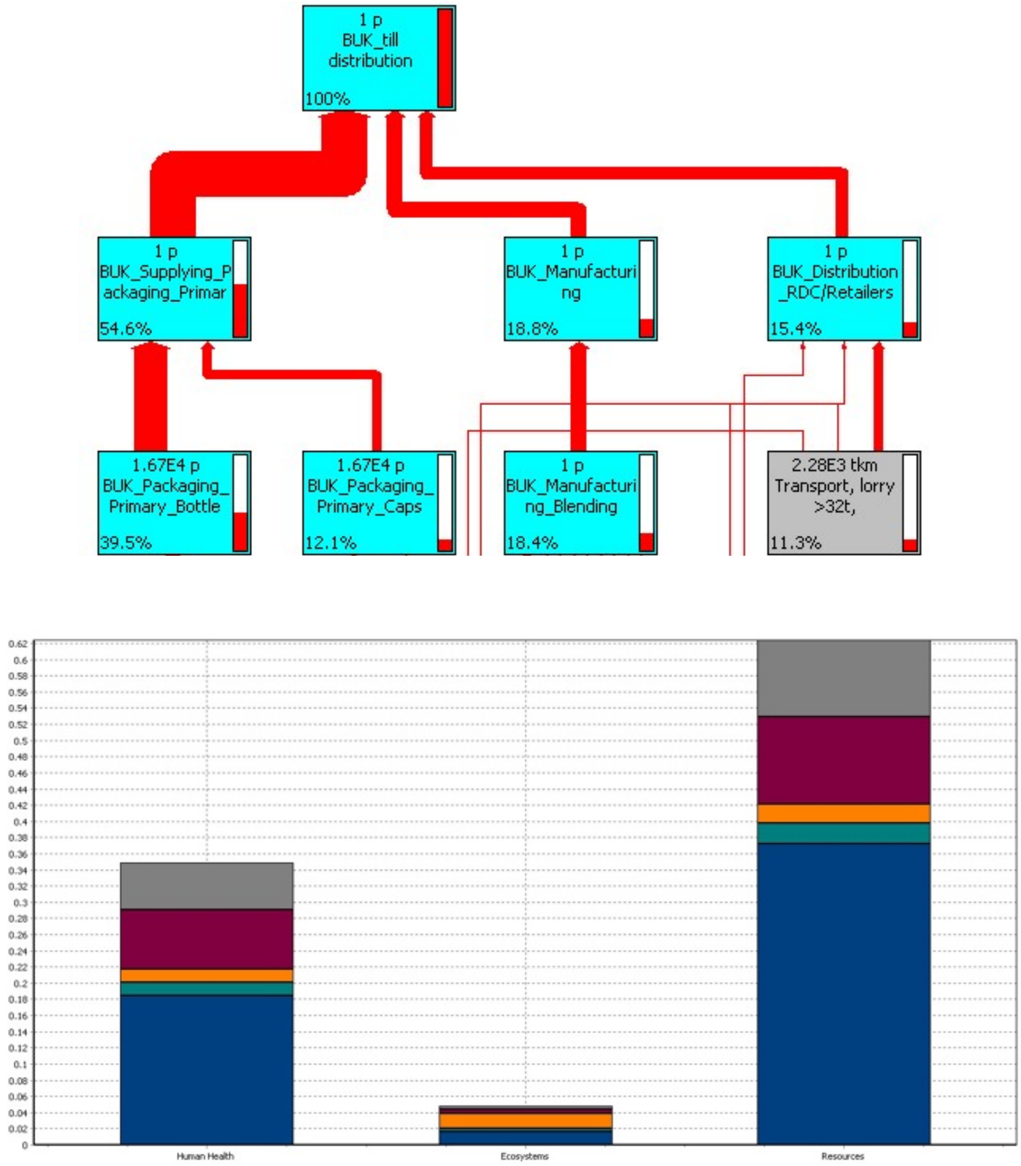


8.4.2. Scenario 2: cradle-to-distribution

The filled bottles of shampoo are stored in the manufacturing site after the production process and before distributed beyond the factory's gate. The impacts from the supplying stage till the shampoo delivering to stores, passing by distribution centres, are reported to highlight the environmental impacts generated in this phrase that are managed by the shampoo manufacturer.

As shown in Figure 8.7, the distribution stage determines the 15.4% of the impacts in this scenario comprehending almost the whole shampoo life cycle, just before use step.

Figure 8.7. Impacts flows (top) and damages (bottom) in scenario Cradle-to-Gate including the distribution step (grey bar). Colour legend: blue for primary packaging production and delivery, green for secondary packaging production and delivery, orange for shampoo ingredients supply, red for shampoo manufacturing, grey for distribution

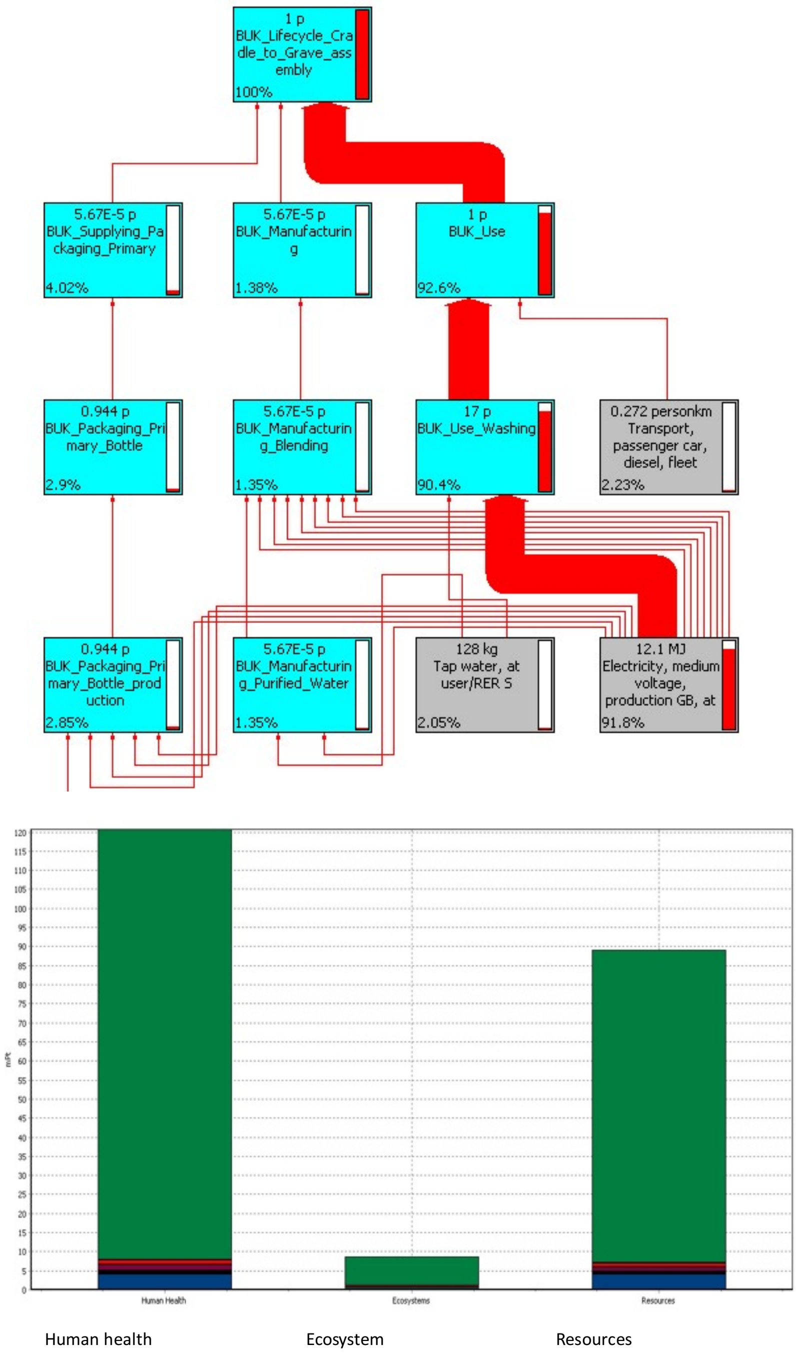


8.4.3. Scenario 3: cradle-to-grave

This scenario presents the environmental performance of the use and disposal stages. The addition of use stage to the previous scenario generating impact flows are shown in Figure

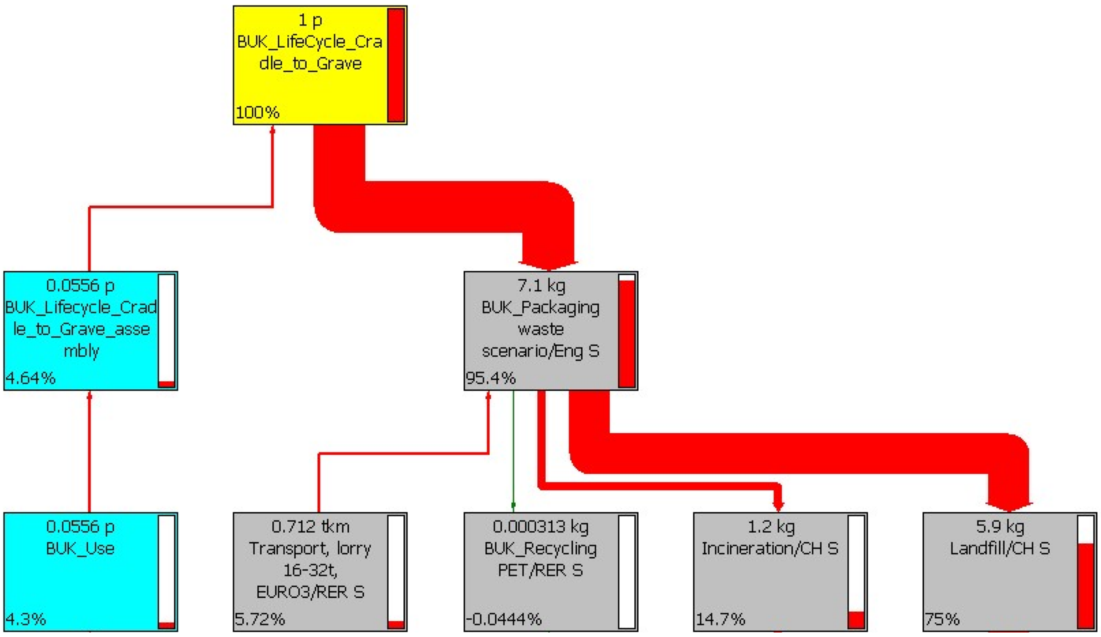
8.8. The impacts generated by use account for more than 92% of the whole life cycle excluding the disposal, which is mainly due to the consumed electricity to heat the water for washing the hair.

Figure 8.8. Impacts flows (top) and damages (bottom) in scenario Cradle-to-Grave, before final disposal, with dominance of use stage (green bar)



The inclusion of the final Disposal stage further influences the calculation results. As shown in Figure 8.9, the disposal (i.e. waste scenario) have more than 95% of environmental impacts that are generated in the whole shampoo product life cycle.

Figure 8.9. Impact flows of the whole life cycle, from supplying to disposal



The final results are inconsistent with previous studies (Koehler & Wildbolz 2009) (PCF 2008), where disposal generates significantly lower amount of environmental impacts. The breakdown of this impact reveals that it is mostly related to the treatment of wastewater, that has been taken from the ecoinvent database, and may not accurately reflect the actual situation. Further analysis will be required about waste management inventory.

On the other hand, if the disposal is ignored, the Use phase dominates the environmental impacts comparable to the previous studies in shampoo(Cullen & Allwood 2009; Dewaele et al. 2006). The significant role of consumers in the generation of environmental impacts has been highlighted and stressed leading to theories and actions for behavioral change, e.g. inviting to consume less water or lower temperature. Some suggestions have also been created for the manufacturer to enhance the product environmental performance:

- Delivering a novel dry-shampoo formula that does not require the use of water.
- Introducing a dispenser that shows the minimum amount of useful product for the given purpose according to manufacturers' investigations.

From a methodological point of view, the following ideas are elaborated from these analytical results for improving the LCA service based system:

Manufacturers proved to be a fundamental and reliable source of data and clarification to conduct the environmental performance evaluation, especially the data inventory can be reused in the same product evaluation context.

Responsiveness by actors in the supply chain to provide necessary information is extremely low or not plausible, although the influence of ingredients supplying is extremely limited in the whole life cycle. Hence, the data protection mechanism is required to build from the perspective of system building, and regulating end users' operation.

Cradle-to-Gate scenario and Distribution are mainly based on primary data, while the definition of Use and partly of Disposal are heavily relied on assumptions and statistics with relevantly high margins of variability (e.g. amount of water consumed per washing a hair, shampoo dosage, preferred temperature, distance from consumer's house to store, rate of recycled/incinerated/landfilled materials at the end of life). This proved that the required data from consumer side is extremely important to reduce the assumptions in the LCA based studies, From the point of client application development, enhancing the user experience on software utilization is required to incentivize consumers to interact with the software. The availability, reliability and transparency of data is another key issue to consider as the impossibility of accounting for every pathway through product life cycle. Then the boundaries excluding certain processes is required to clarify.

8.5. Summary

This chapter introduces the environmental impact assessment of the shampoo product with LCA in three different scenarios. In the Cradle-to-Gate scenario, the production of primary packaging (especially bottles) and all ingredients supplying accounts for the majority of generated environmental impacts, while in the Cradle-to-Grave scenario, the disposal process totally dominates the negative impacts involved in the shampoo product life cycle. Moreover, the Cradle-to-Distribution scenario are not of high environmental impacts.

The elaboration of LCIs in the examined scenarios are mainly based on the manufacturer's data and the existing databases. In order to conduct a reliable LCA, users of the LCA service based system are required to have a broad view of the product to evaluate and interact with the stakeholders, particularly the communication with consumers.

Missing data have been gathered by ecoinvent database, especially to fill the gaps at the supplying stage. The results are not expected to be significantly different compared with the present results by using existing LCIs in relation to the scopes of this phase of the study. Nevertheless, the environmental impacts of other flows, e.g. energy provision and waste management, may consistently vary. Therefore, the interaction with local municipalities and the full description of energy mix by the provider is suggested for the system users.

Chapter 9: Development of a sustainable flooring product using sustainable production support toolbox

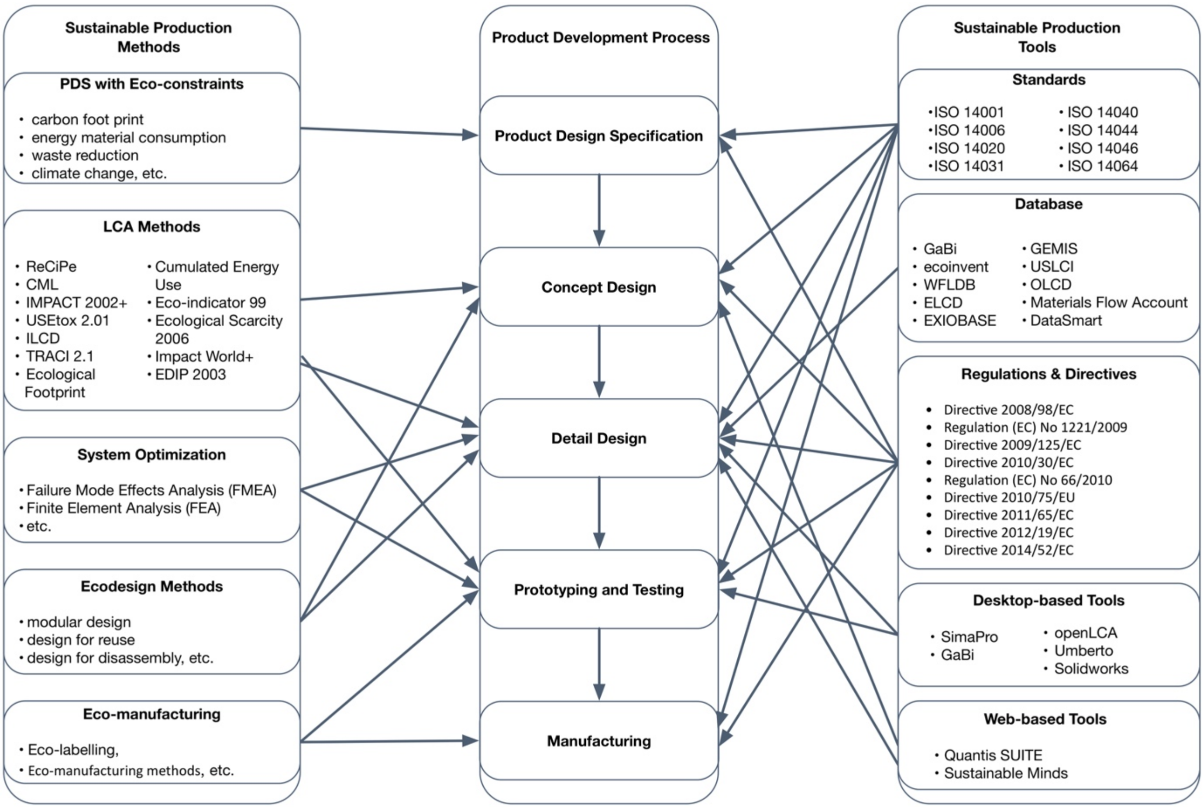
9.1. Explanations of the framework

The developed toolbox aims to provide state-of-art technologies and tools supporting the LCA and sustainable production activities. The key objective of this toolbox is to offer the main sustainable production support technologies including the methodologies (e.g. ReCiPe, CML), LCA software (e.g. SimaPro, openLCA), and LCI databases (e.g. ecoinvent), which aims to help end-users to select the feasible evaluation methods, and non-LCA experts to master the LCA support tools. A wide range of sustainable production support tools have been investigated in the toolbox development phrase, they can be integrated into the product development process according to the application scope and requirements, as illustrated in Figure 9.1.

The sustainable production methods

- Elaboration of product design specifications (PDS) with sustainability constraints, such as reduction of product carbon footprints, energy/material consumption, waste, and contribution to climate change.
- Product lifecycle impact assessment methods, such as ReCiPe, CML.
- Product failure analyses, such as failure mode and effect analysis (FMEA), and finite element analysis (FEA).
- Ecodesign methods, such as modular design, design for re-use, design for recycling.
- Eco-manufacturing, eco-labelling.

Figure 9.1. Integration framework for applying the sustainable production support toolbox into product development process



The sustainable production tools

The regulations, directives, and standards presented in the integration framework are generalized tools applicable to products manufactured in the EU. When applying this framework to the specific product development, regulations and standards related to the product characteristics and manufacturing procedures should be considered. For example, in the case of developing sustainable LED products in the EU, the regulations and standards related to the resource efficiency of luminaires, and recycling of Waste Electrical and Electronic Equipment (WEEE) should be referred to.

- Standards are requirements related to the production activities and quality of products characteristics.
- Regulations and directives are regulatory rules related to ecodesign, recycling of wastes, pollutant emissions and reporting at voluntary and legislative level.

- Databases are data sources to support LCA and environmental performance reporting.
- Software tools (desktop based) are used to select sustainable materials and conduct comprehensive LCA.
- Software tools (web based) are used to conduct screening level sustainable design, environmental materials selection, and simple LCA.

The product development process considered in this framework includes the elaboration of PDS, conceptual design, detail design, prototyping and testing, and manufacturing, as illustrated in Figure 9.1.

In the PDS elaboration phase, the sustainable constraints are derived from various sources such as relevant directives, regulations, ecodesign guidelines, standards. These relevant sustainable constrains are integrated into the PDS.

In the conceptual design phase, in order to meet the PDS, several design concepts are created, and then evaluated against the PDS criteria. Relevant standards are used to set-up the evaluation criteria. The LCA is conducted during the concept design phase, because the product information is not detailed in this phase, a screening-level evaluation is preferred. The LCA software for simple and fast analysis is adopted.

In the detail design phase, the product is further refined from the concept obtained in the conceptual design phase. The major tasks include selection of components, material selection, and the product system configuration. Several software tools are utilized to select the components and conduct the detail design task. Relevant standards are also referred during this phase to ensure the product quality and to meet the sustainable specifications.

In the prototyping and testing phase, the prototype of the product is produced and tested, and relevant eco-manufacturing/eco-labelling methods and strategies are utilized in order to ensure the product to meet the required sustainable constraints and the quality according to the referred standards. Feasible testing tools are utilized to examine the product quality. The LCA methods, ecodesign methods and product failure analysis methods are all applied in this phase. Unlike the LCA conducted in the conceptual design phase, a more comprehensive LCA is required to implement at this stage, because the product prototype is completed and hence more detailed information about the product is available.

In the manufacturing phase, relevant eco-manufacturing and eco-labelling methods are applied to reduce waste, material, and impact on the environment, and these methods and strategies can be elaborated from the findings of LCA. Relevant standards are also followed at this stage to ensure product quality.

9.2. Building product design specifications

Resulting from the Sustainable Flooring Products Development project (No. 2015DFA51330), the prototype of a raised access floor system has been manufactured by the project partner in the UK. The sustainable flooring system is manufactured with Sheet Moulding Compound (SMC) and metal, and this case study introduces the process of developing this product system with the proposed integration framework and state-of-the-art tools.

The following sustainable constraints are built during the PDS phase:

- The product needs to use the least number of components possible, whilst maintaining the required quality.

- Extending the product lifespan. The product should be durable and components should have easy access for installation and repair.
- Application of ecodesign methods, such as modular design, design for easy repair and upgrade, design for disassembly, design for reuse.
- Designing the product system that facilitates components' recovery for re-use, re-manufacture and recycle.
- Using the minimum type of materials, which facilitates the sorting of components for reuse and recycling when the product reaches its end of service life.
- Using low environmental impact materials and manufacturing processes.
- Avoiding the use of special tools for disassembly, non-detachable joints (welded or glued joints), and toxic materials.

The above PDS are derived from relevant directives, regulations and standards related to sustainable production in the EU. For example, the Environmental Impact Assessment Directive demands the companies to implement environmental impact assessment towards product life cycle, and to report the pollutant emissions related to manufacturing (European Commission 2014). Derived from this directive, the 'Use low environmental impact materials and manufacturing processes' is listed in the PDS.

9.3. Conceptual design

In the conceptual design phase, the product concept was developed in compliance with the sustainable PDS and regulations, directives, and standards that are directly linked with the flooring product quality and regulatory requirements, which are presented in Table 9.1.

Table 9.1. The sustainable PDS, regulations, directives, and standards for the sustainable flooring product

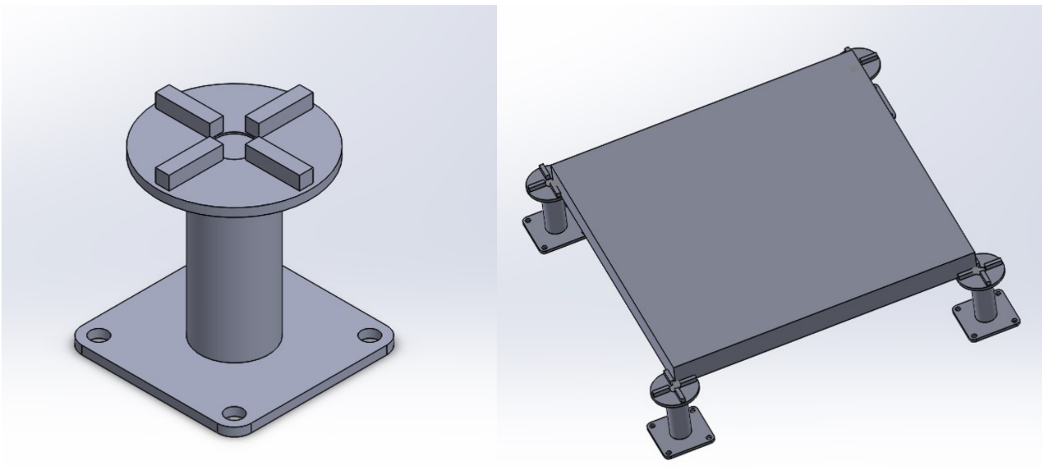
Compliance with the sustainable PDS	
Use fewer components and low environmental impact materials	The glass fibre filled polymer is used to produce the floor panel, because of its high performance in strength, cost and fire resistance properties. The material of the pedestal unit and stringer is steel, and it can be re-used or recycled.
Increase product lifespan	Several strategies have been implemented to increase the flooring product lifespan: 1) increase the reliability of the product, 2) design the product for easy disassembly, 3) long warranty, 4) design a scheme to encourage the recycling of components.
Easy to install the product	The flooring product system consists of a pedestal and a pedestal cover. The cover is placed on the top of the pedestal circular plate, which supports the accurate installation for the floor panel.
Reduce the weight	The weight of the traditional raised access floor panel is approximately 11kg, and the new design product should be lighter, which also reduces transportation costs.
Compliance with the sustainable regulations, directives, standards	
EU Waste Framework Directive	The manufacturer of raised access floor system has registered with a waste framework scheme.
EU Industrial Emissions Directive and Environmental Impact Assessment Directive	The manufacturer needs to assess and report environmental performance related to manufacturing process and product life cycle, so the detailed LCA is required.
BS 476-Part 6 & 7 – Fire Tests on Building Materials and Structures	BS 476 Part 6 requires the floor panel to achieve Class O on fire propagation performance (BSI 1989), and BS 476 Part 7 requires the floor panel to achieve Class 1 on performance of resisting surface spread of flame (BSI 1997). Hence, the fire resistance test is required.
BS EN 12825 – Raised Access Floors	It states that the floor system must pass the working load test by measuring the deflection/deformation values, and the limited value is rated as Class A (2.5 mm), Class B (3.0 mm), Class C (4.0 mm) (BSI 2001). Hence the deflection/deformation measurement is required.

SolidWorks 2015 is adopted to design the raised access floor system as it offers the modelling function and the screening-level life cycle assessment. In addition, the BS EN 12825 requires the strength test (BSI 2001), once the modelling of the raised access floor system is completed, FEA can be conducted to examine the system's strength performance in the SolidWorks 2015.

SMC materials are selected for producing floor panels in this project, because of the strong performance in mechanical properties, fire resistance, and stiffness. Its physical properties are presented in Table 9.2.

The modelling of the raised access floor system involves the design of a floor panel, a pedestal, and a pedestal cover, which are shown in Figure 9.2. The dimensions of the pedestal unit and the floor panel are introduced in Table 9.2, which meet the criteria of the British Standard 12825 and PSA raised access floors performance specification. The pedestal design prevents excessive movement of the panel, by which the stability of the raised access floor system is strengthened.

Figure 9.2. Conceptual design for the pedestal unit and the raised access floor system



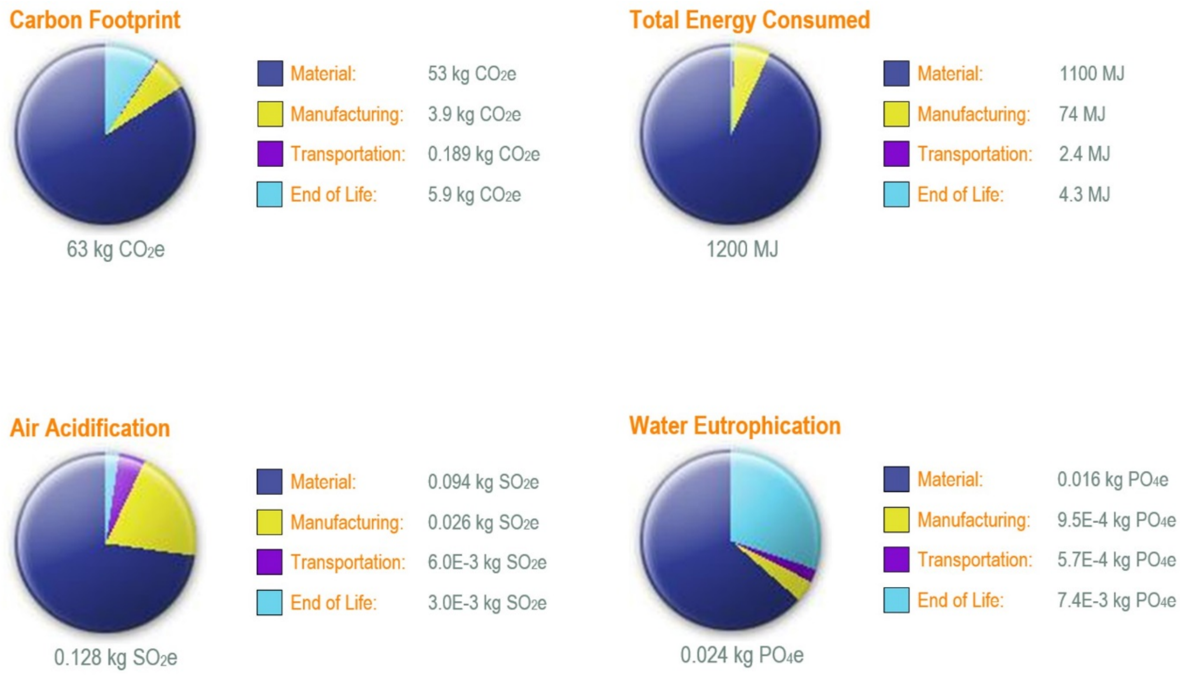
The standard size for raised access floor panels is adopted to design the floor panel in this project, and its dimensions are also presented in Table 9.2. The weight of the floor panel is 25.92 kg, which is obtained by calculating the design dimensions and SMC density, which violates the weight constraint (≤ 11 kg) defined in the PDS.

Table 9.2. Dimensions in conceptual design and the SMC physical properties

Items	***Values***
Component dimensions in conceptual design	
Height of pedestal	100 mm
Square base plate	100 mm x 100 mm
Diameter of circular plate at the top	90 mm
Size of the floor panel	600 mm x 600 mm x 40 mm
Weight of the floor panel	25.92 kg
Physical Properties of SMC	
Density of the selected SMC	1800 kg/m^3
Flexural modules	1.3 GPa
Poisson's ratio	0.3
Yield strength	250 MPa
Tensile strength	150 MPa

CML and TRACI are methodologies offered by the LCA package of SolidWorks 2105. The CML method is adopted in this phase, and the screening-level results show that the materials contribute major negative impacts in the four environmental impact categories: 84% in Carbon Footprint, 91% in Total Energy Consumed, 73% in Air Acidification, and 66% in Water Eutrophication. The pie chart of the LCA analytic results are shown in Figure 9.3. However, the results only show the total negative impacts in the limited environmental impact categories, and the breakdowns of each impacts are not described, therefore user cannot identify the specific elements of the composites, or production processes causing high negative impacts. Consequently, the targets for design optimization and manufacturing improvement are not clearly shown.

Figure 9.3. The LCA results by adopting CML methodology in SolidWorks 2015



9.4. Detail design

A key objective in the detail design phase is to mitigate the constraints identified in the concept design phase. Therefore, reducing the weight of the floor panel is the prioritized task in this phrase. In addition, multiple advanced tools are utilized to perform detail design for the prototype and carry out a delicate LCA.

9.4.1. Refinement of the raised access floor system

In order to achieve an effective design, the floor panel requires strong outer edges with the side of the panels connected by ribs, hence, the strategy of designing ribs for the floor panel is adopted. The optimum design of the floor panel has same size squares with 3 mm ribs between them, with 3 mm ribs between them, and the layout and dimensions of these rectangles are shown in Figure 9.4 and Table 9.3, respectively. The thickness of the floor panel is cut from 40 mm to 30 mm in the design comprising squares' size and ribs' thickness, therefore the strength performance of the floor panel is reduced. The solution of placing a steel stringer under the floor panel is adopted, as this design not only sustains the strength performance of the floor system, but also provides the facility of recycle or reuse for the steel stringer. The stringer design is shown in Figure 9.4, and its dimensions are shown in Table 9.3.

With this optimum design, the total weight of this raised access floor system has been reduced to 8.06 kg, which is lighter than the average weight of a raised access flooring product. The refinement of the raised access floor system is presented in Figure 9.4.

Figure 9.4. The design of the floor panel and stringer

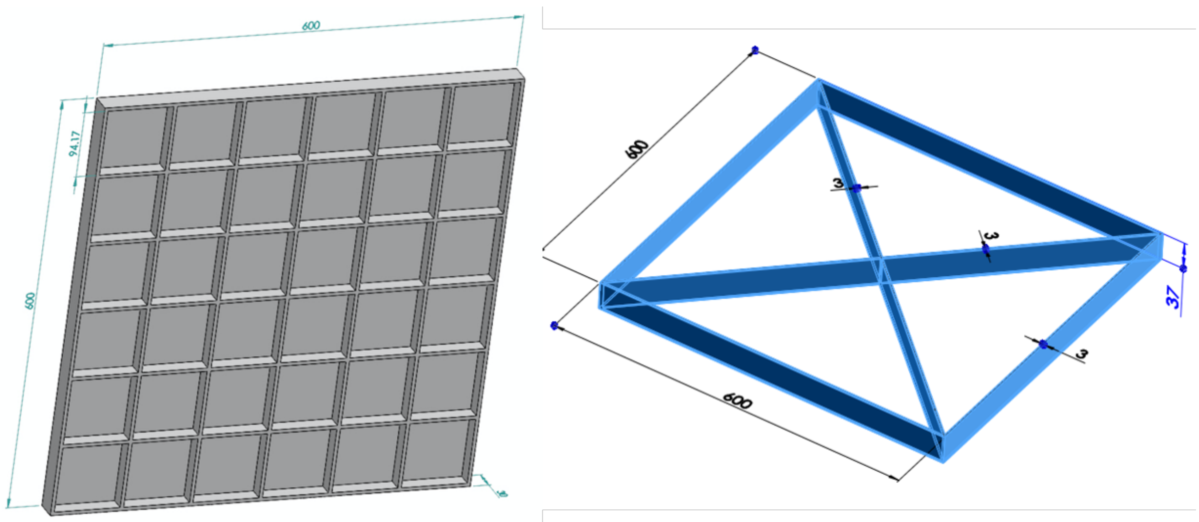


Table 9.3. Main components' dimensions and weight in detail design phrase

Item	***Value***
Component dimensions and weight in detail design	
Square	94.7 mm x 94.7 mm x 94.7 mm
Thickness of ribs	3 mm
Thickness of the floor panel	30 mm
Size of the stringer	600 mm x 600 mm x 37 mm
Thickness of the string edge and beam	3 mm
Component weight for detailed design	
Floor panel	3.52 kg
Stringer	3.55 kg
Pedestal unit	0.99 kg
Total mass	8.06 kg

9.4.2. LCA of the raised access floor system

According to the regulatory requirements, environmental performances of the raised access floor system are required to report. In addition, the materials and manufacturing processes with high negative impacts through the product life cycle should be identified, with the aim of building optimization strategies for design iterations and production processes.

The environmental impact assessment of the raised access floor system is implemented by using the SimaPro (version 8.1.1) with the ecoinvent (version 3.2) database. ReCiPe methodology are adopted to conduct LCIA under the Cradle-to-Grave scenario towards the raised access floor system in this research. The version of ReCiPe methodology is Endpoint (H) V1.12 / Europe ReCiPe H/A (provided by SimaPro 8.1.1).

9.4.2.1. Life cycle modelling

Considering the available data and objectives of this research, the examined life cycle processes of the raised access floor system include: Materials, Production, Distribution and End of Life, which are described as follows:

Materials: The main ingredients of SMC are glass fibre and polymers. As the formulation of the adopted SMC is not disclosed, other ingredients including additives and fillers have to be disregarded. The pedestal unit and stringer are manufactured with normal steel. The floor panel is packaged with wood pallets and PVC films.

Production: The examined processes of producing SMC include: heating of resin, and moulding, which follows the information of the SMC product specification (Menzolit 2016). The examined processes of producing the floor panel include: heating, cutting ribs and edges. The examined processes of producing the pedestal unit and stringer include: extrusion of steel, and steel turning. The main process not covered in this phrase is the production of glass fibre, which usually include raw material extraction, glass melting and refining, and fibre forming and finishing (EPA 1985).

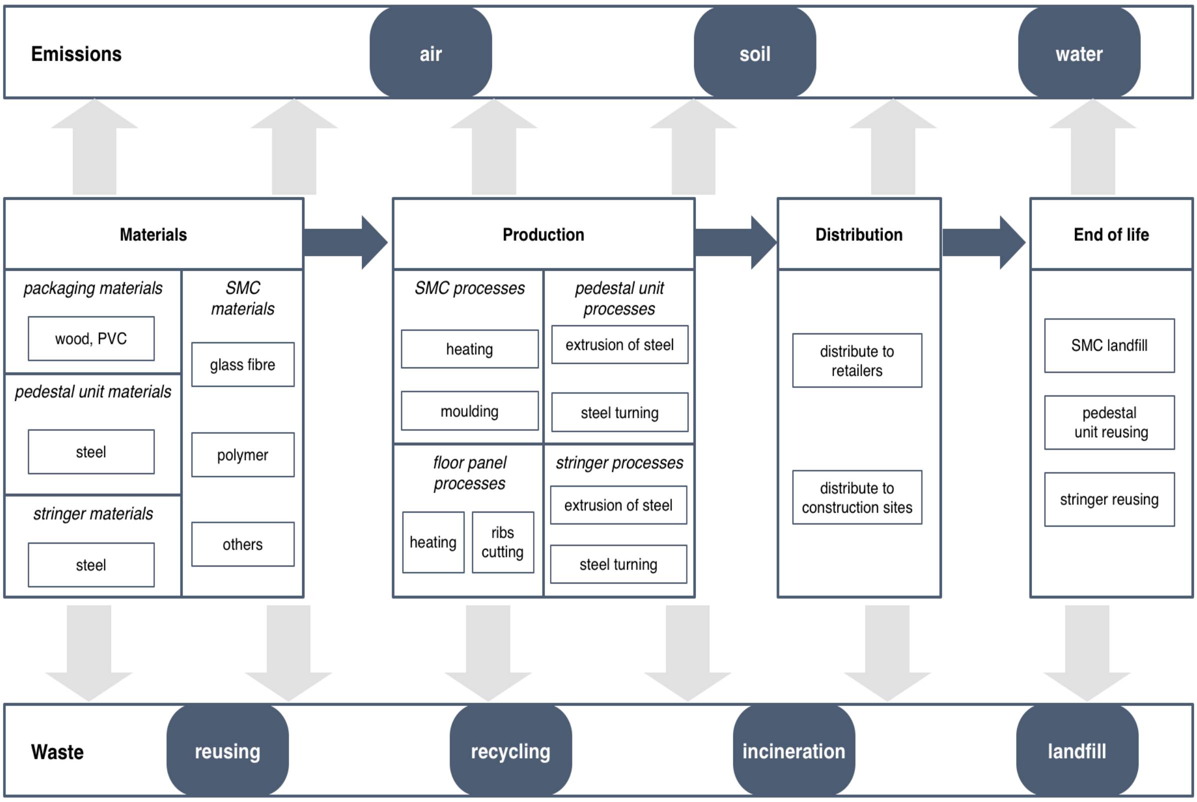
Distribution: The examined distribution scenarios are from manufacturing site to retailers or construction sites in England, and this distance is an average of 200 km (suggested by the floor panel prototype manufacturer). The neglected distribution scenarios are the delivery of SMC ingredients from suppliers to manufacturers, and the delivery of packaging materials from suppliers to flooring product manufactures.

End of Life: This study refers for the waste treatment and management figures in England that are provided by the UK DEFRA (DEFRA 2015), and these statistics are compiled to comply with EC Waste Framework Directive (2008/98/EC). In this study, the waste treatment involves glass, steel, plastics, wood and PVC, and the percentages of recyclable materials are presented in Table 9.4. This means that the environmental impact evaluation of this scenario adopts the recycling percentages of each type of materials that are used in the product system. Hence, based on the descriptions presented above, the core activities and boundaries involved with the raised access floor system life cycle are mapped in Figure 9.5.

Table 9.4. Percentages of recyclable materials in the waste scenario of England

Material	***Waste treatment***	***Percentages***
Glass	Recycling glass/RER U	46.5%
Steel	Recycling steel and iron/RER U	46.6%
Plastics	Recycling mixed plastics/RER U	2.7%
Wood	Recycling/recovery in the England	42.3%
PVC	Recycling PVC/RER U	2.7%

Figure 9.5. Life cycle modelling of the raised access floor system



9.4.2.2. Life cycle inventory building

SMC ingredients' masses are obtained according to the material percentage revealed in the SMC production specification. The values of delivery distance, packaging weight, and machine energy consumption are provided by the manufacturer. Missing data is supplied by the ecoinvent 3.2 database, for example, LCI of pedestal unit, emissions of lorry transportation, electricity voltage for production in the England. The functional unit adopted in this study is one piece of raised access floor system, and the values of the inventories are presented in Table 9.5.

Table 9.5. LCI values of the raised access floor system

materials/processes	***values***	***units***
glass fibre	1.87	kg
polymer	4.35	kg
Stringer	3.55	kg
pedestal unit (steel)	0.993	kg
packaging (wood pallet)	0.2	piece
packaging (film)	0.47	kg
transport distance	200	km
transport weight	10	kg
heating	2.1	kWh
cutting	0.3	kg

9.4.2.3. Life cycle impact assessment

The network of analytical results is shown in Figure 9.6. A 2.4% cut-off is applied, which means any impacts' percentage less than 2.4% is not shown in the network diagram. Figure 9.7 only shows the partial network diagram to highlight the key flows of materials and processes, as the original completed diagram is too large for this paper layout. Each box in the network shows the name, weight, and percentage of the process/material in the whole life cycle, and all the numerical information is indicated by the thermometer within the box.

As Figure 9.7 shows, within the total impacts, the major negative impacts are generated by the Materials (56.13%), and the Production (24.53%), Packaging (18.4%), and End of Life (3.52%) share 46.45% impacts in total. The distribution impacts are only shown (0.33%) with at least a 1.3% cut-off criteria.

Within the Materials, glass fibre, polyvinylchloride, and steel contribute 26.7%, 21%, and 8.43% impacts respectively. It means the two components, the floor panel and pedestal unit, are allocated 47.7% and 8.43% impacts. Furthermore, among the materials producing the floor panel, the main impacts are caused by Nylon 6-6 (21.2%), which is also the main ingredient for producing the glass fibre.

Focusing on the Production, the SMC moulding (13.8%) and steel extrusion (7.47%) and turning (3.26%) have the highest environmental impacts. Within impacts caused by the packaging, the wood pallet and PVC film share 16.3% and 3.05% respectively. As the wood pallet is reusable, the negative impacts related to it are linked to its production stage (16%).

In terms of the End of Life for the raised access floor system, the environmental impact (3.52%) is not remarkable compared with the impacts that occur in Materials, Production, and Packaging, which shows that the adopted materials' recyclable performance is not remarkable.

Figure 9.6. Network diagram of the LCIA results with a 2.4% cut-off criteria

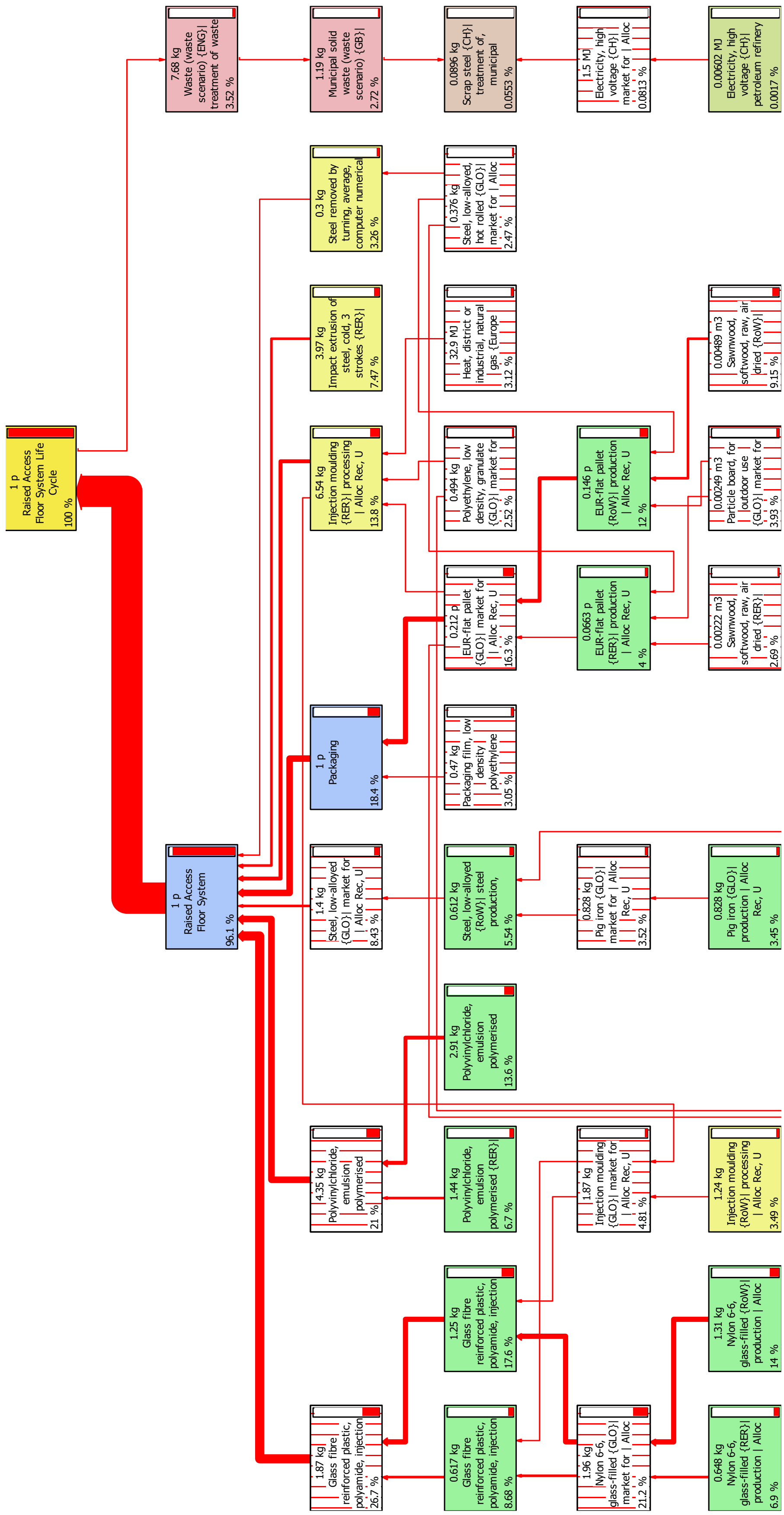


Figure 9.7 shows the weighting results of the raised access floor system in endpoint impact categories, which include Human Health, Ecosystems and Resources. It shows that Resources category (about 2.02 Pt) has the highest negative impacts, and the steel, polyvinylchloride, and glass fibre reinforced plastic cause the top 3 negative impacts, which are also the top 3 impact sources for the Human Health category (about 1.8 Pt). The Ecosystems category (about 1.5 Pt) contributes relatively small negative impacts, and the top 3 impact sources are Packaging, glass fibre reinforced plastic, and polyvinylchloride.

Figure 9.7. Weighting results in ReCiPe endpoint impacts for the raised access floor system

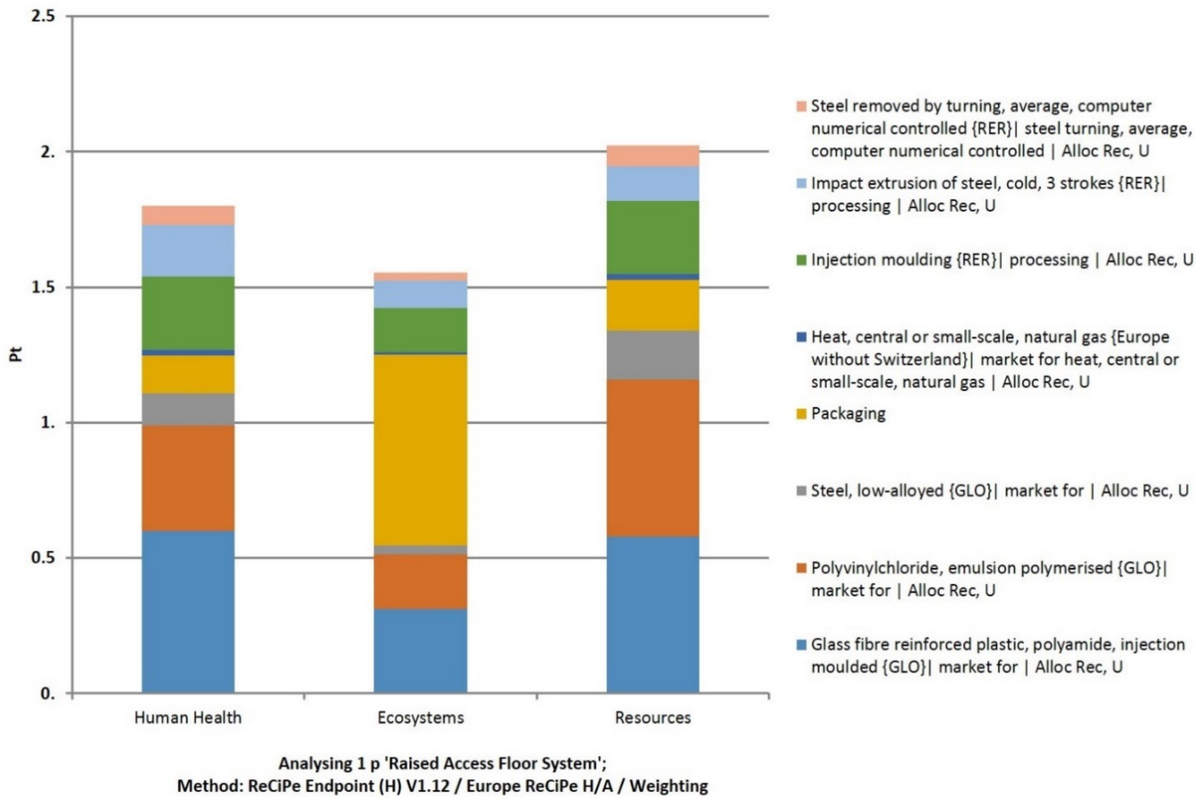


Table 9.6. Mass of main flows with high environmental impacts, expressing benchmarking values for optimum design and production

Flows	*Unit*	*Human Health*	*Ecosystems*	*Resources*	*Total*
Glass fibre reinforced plastic, polyamide, injection moulded {GLO}| market for | Alloc Rec, U	Pt	0.5997	0.3134	0.5779	1.491
Steel, low-alloyed {GLO}| market for | Alloc Rec, U	Pt	0.119	0.0337	0.1822	0.3348
Polyvinylchloride, emulsion polymerised {GLO}| market for | Alloc Rec, U	Pt	0.3909	0.2006	0.5814	1.1729
Packaging	Pt	0.1396	0.7033	0.1865	1.0294
Injection moulding {RER}| processing | Alloc Rec, U	Pt	0.2718	0.1613	0.268	0.7012
Impact extrusion of steel, cold, 3 strokes {RER}| processing | Alloc Rec, U	Pt	0.1888	0.101	0.1278	0.4177
Steel removed by turning, average, computer numerical controlled {RER}| steel turning, average, computer numerical controlled | Alloc Rec, U	Pt	0.0723	0.0302	0.0797	0.1822
Heat, central or small-scale, natural gas {Europe without Switzerland} | market for heat, central or small-scale, natural gas | Alloc Rec, U	Pt	0.0183	0.0102	0.021	0.0496
	Pt				5.3787

9.4.2.4. Interpreting the analytical results

As the End of Life and Distribution share relatively small negative impacts (3.85%, 0.2155 Pt) in the life cycle of the raised access floor system, the target of design improvement should be placed at the Materials (56.13%, 3.13 Pt). The following strategies are created to achieve this objective through exploring the findings of the LCIA:

Table 9.6 shows the mass of negative impacts caused by the main flows within the three environmental impact categories, which could be used as benchmarking values in the next iterations of design. For example, in the case of investigating alternative main materials, the total mass (5.3787 Pt) of negative impacts can be used as the key benchmarking value to examine the potential material's environmental performance.

The Materials has the most negative impacts, and the Distribution stage has the smallest negative impacts, which is consistent with the analytical results offered by SolidWorks 2015 in the conceptual design phase. It shows the design improvement strategy on reducing the mass of materials is correct, and in order to achieve further design improvement, the design on the ribs and rectangles of floor panel could be elaborated, for example, reducing the thickness of ribs, or increasing the depth of each rectangles.

Glass fibre reinforced plastics have the most negative impacts among all the materials, therefore the alternative improvement strategy is to select the SMC composites with low glass fibre and polyvinylchloride in the SMC formulation, or to reduce the percentages of Nylon 6-6 in the glass fibre formulation, which contributes the highest impacts (21.2%) as shown in Figure 9.7.

The Injection moulding process causes the highest negative impacts among all the production processes, so an improvement strategy would be to cut the overall moulding cycle time, and improve the mould speed.

It will be necessary to evaluate the proposed design improvement strategies, in order to test whether they can be implemented without compromising the physical properties required by the PDS, regulations and standards (e.g. fire resistance, strength). For example, although the recycling performance of SMC is low, other possible alternative materials are required to meet the fire resistance requirements.

The Sustainable Flooring Product Development project (No. 2015DFA51330), is an ongoing project, and diverse materials with different structures have also been proposed to design the raised access floor system, for example, paper core encapsulated by composite materials, balsa chipboard encapsulated by composite materials, and foam core encapsulated by composite material. The LCA will be used to evaluate the environmental performance of all these design solutions, and the solution with the lowest environmental performance would be commercialised in the European market.

9.5. Prototyping and testing

In this phase, the prototype of the raised access floor system was tested and analysed to confirm that the final real product could meet the PDS, and pass all the tests identified in the conceptual and detail design phases, which include fire and strength tests. The prototype of the raised access floor system is shown in Figure 9.8. The fire safety test must be conducted under controlled conditions, and by an external fire safety test company, which is not reported in this study.

Figure 9.8. The prototype of the raised access floor product system (left) and the back of the floor panel (right)

9.5.1. Finite Element Analysis (FEA)

Finite Element Analysis is the laboratory method examining strength performance, and SolidWorks 2015 is selected to assess the strengthen performance of the product in this phrase. The finite element methods used for examining the raised access floor system is a static and a linear system so that the linearity of relationship between the force and deflection of the floor system can be identified. The finite element method worked by breaking the computer model of the raised access floor system into smaller elements through the use of nodes and elements. Physical and geometric properties are allocated to the elements, and loads and displacements are applied to the nodes.

Two key indicators of FEA strength simulation are max yielding stress and max deformation. In terms of the ‘Maximum yielding stress criterion’, also called ‘Maximum distortion energy theory’, a flooring product starts to yield at a location when the maximum yielding stress becomes equal to the yielding strength, which is used as the stress limit. For the flooring product developed in this project, the yielding strength is obtained according to the physical properties of the floor panel and stringer. The maximum yielding stresses of the panel and stringer are required to be less than 94MPa and 250MPa, respectively, while the maximum deformation of the panel and stringer should be lower than 2.5mm. According to the requirements of British Standards BSEN 12825:2001 (BSI 2001) and Platform Floors (Raised Access Floors) Performance Specification (PSA Specialist Services 1990), 3000 N and 6000 N working loads are required to place on the central and edge of the floor system.

As Figure 9.9. - Figure 9.13. show, all the deformation values are less than 2.5 mm with 3000 N loading forces on the central and edge of the panel and stringer, which satisfy the flooring product's deformation criteria of Class A, as defined by the British Standard requirements. Therefore, under 300 N of working load, the designed flooring product is able to work properly within the scope of elastic deformation.

Figure 9.9. Max yielding stress for the floor panel and stringer with loading 3000N force at the central panel

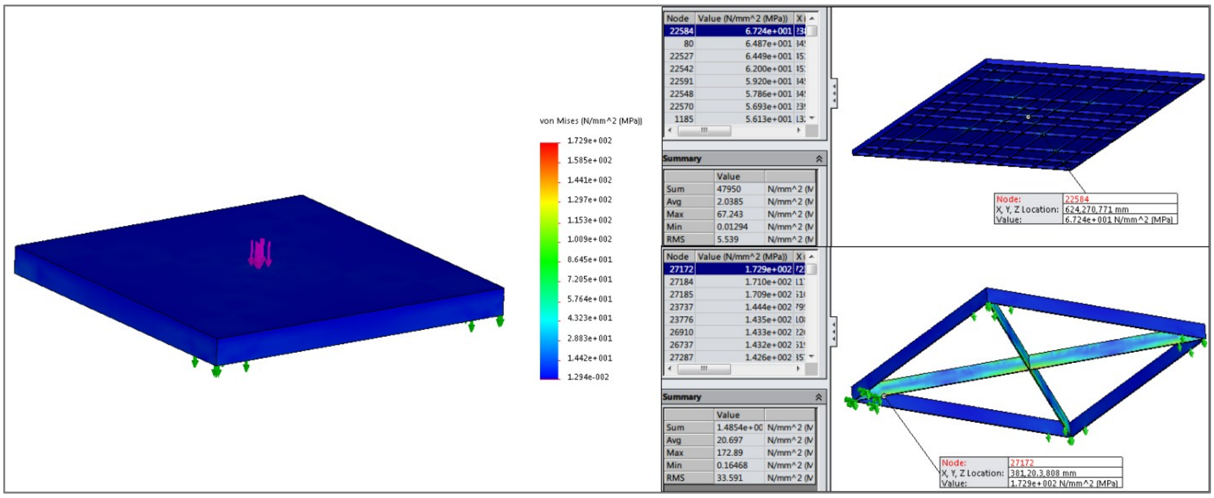


Figure 9.10. Max deformation for the floor panel and stringer with loading 3000N force at the centre panel

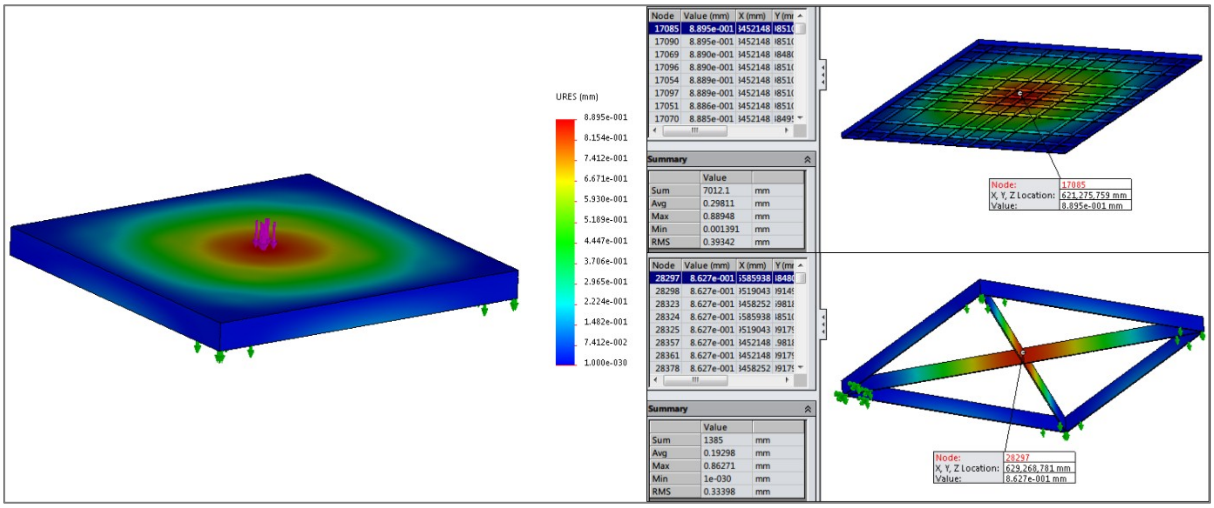


Figure 9.11. Max yielding stress for the floor panel and stringer with loading 3000N force at the outer edge of panel

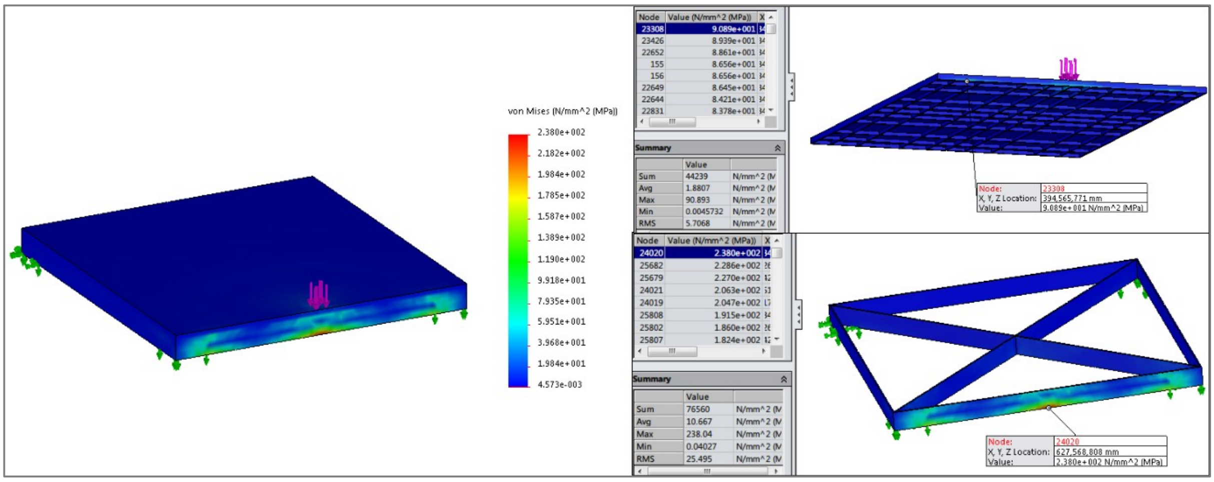
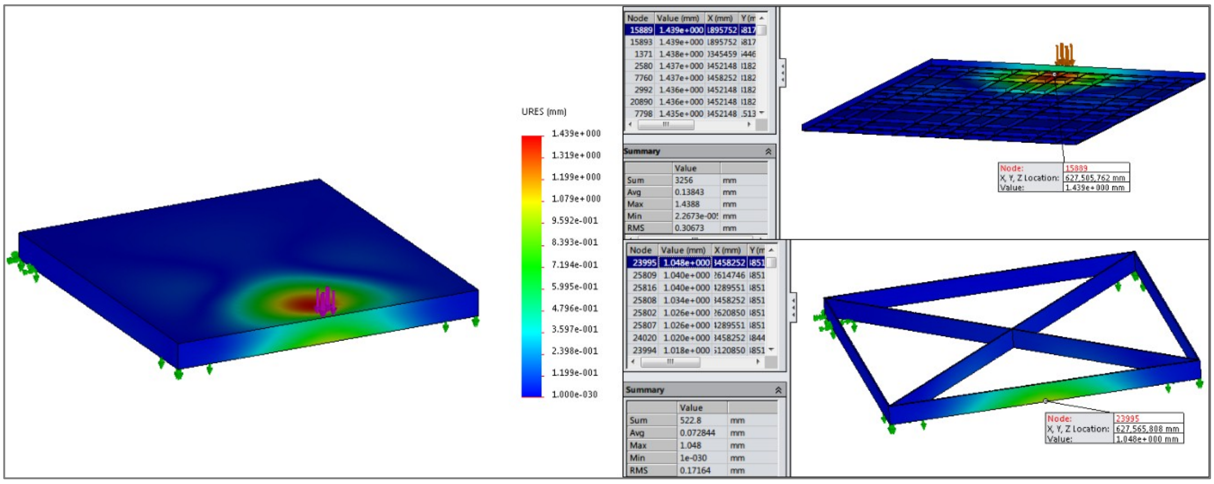
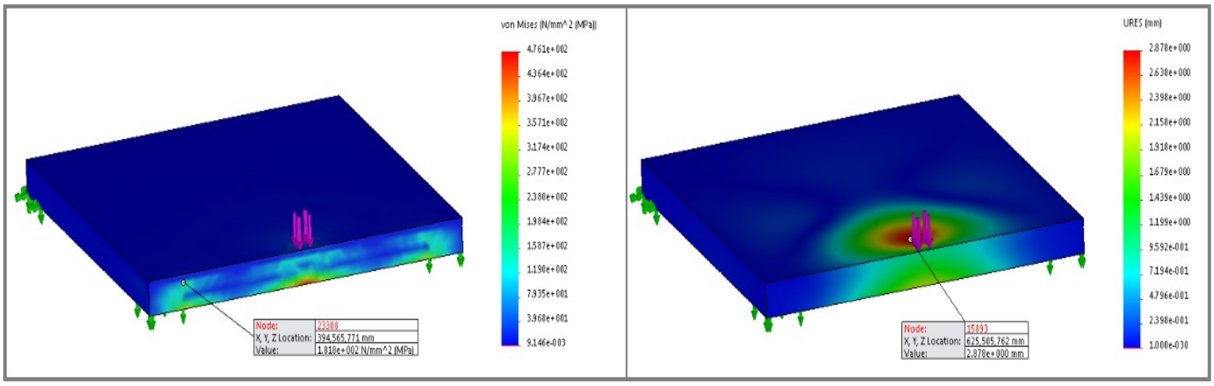


Figure 9.12. Max deformation for the floor panel and stringer with loading 3000N force at the outer edge of panel



As Figure 9.13 shows, under 6000 N of ultimate working load, the maximum yielding stress and maximum deformation of the panel and string exceed the criteria of strength and deformation for the flooring products, therefore the floor panel will be broken down.

Figure 9.13. Max yielding stress and deformation for the floor panel and stringer with loading 6000N force at the outer edge of panel



9.6. Strategies for supporting sustainable manufacturing

Having completed the theoretical test with FEA, the design of the raised access floor system will meet the regulations, standards and PDS that have been incorporated in the conceptual and detailed design phases. Therefore, the flooring product will be produced by the project partner. In order to achieve the sustainable production, the following recommendations have been made according to the findings that are identified in the detailed LCA, conceptual and detail design phases:

- Avoid unnecessary heating time.
- Simplify the manufacturing process and use fewer processes, in order to reduce energy consumption and waste.
- Establish the recycle system for pedestal units and stringer, and provide information about how and where to dispose of the product.
- Increase the reuse rate of the wood pallet.
- Use local suppliers in order to reduce the impacts caused by the distribution of the product.
- Implement a long-term warranty.
- Register with an Environmental Management System (EMAS or ISO 14001) to improve environmental performance of the company's main activities.

9.7. Summary

This chapter introduces a theoretical framework demonstrating the LCA oriented product development methodology. The novelty of this proposed methodology lies in utilising LCA analytical results as benchmarking values to examine environmental performance in the design iterations, and distilling LCA findings into methods and strategies to reduce the negative environmental impacts and improve resource efficiency in the production process.

This methodology's feasibility and functionality is examined through designing a successful sustainable raised access flooring product, and the whole design process is reported in this chapter. The floor panel has been designed with same size squares, which achieve 44%

weight reduction compared with the traditional raised access floor panel. The prototype passed the strength test and met environmental requirements stipulated by the regulations and standards on manufacturing floor products in the EU and UK market. ReCiPe methodology and SimaPro software are adopted to evaluate the life cycle environmental performance of the flooring product, the results of which show that the major negative impacts are related to the SMC material and moulding process.

Chapter 10: Conclusions and future research

10.1. Contributions of this research project

Contribution to LCA technology

This thesis presents the investigations on three major domains of LCA: methodologies, software, and database. The characteristics of almost all the existing LCA methodologies are examined and presented in this study, which not only include the well-established CML, and ReCiPe, but also cover the emerging methodologies and initiative: IMPACT World+, LC-Impact, PEF. Moreover, the environmental impact categories at midpoint and endpoint level are reviewed to build the selection rules. Responding to the study objective which emphasises to develop a new web LCA service system beyond the desktop operating environment, critical review is carried out to investigate the advantages and drawback of the existing LCA related software and systems. The findings of this review not only clarify the ecosystems of LCA tools, but also identify the major theoretical and practical challenges for LCA practices, which include LCI data gathering and management, flexible and efficient calculations, etc.

One of the key novelties of this research is that the product environmental performance assessment solution and its implemented LCA service platform, which has the capacity to support the gathering of primary life cycle data, management of LCI data, and high efficient LCA based calculation. The core component of this platform, web based product assessment system, is the first tool performing the powerful and flexible LCA calculation across web and mobile platforms. In addition, other support applications describe a new scenario to address challenges involved with environmental performance assessment. The proposed database structure is also a novel study that clarifies the SQL format database for LCA, as the existing professional LCA application still rely on the database technologies adopted in the context of desktop operating environment. The developed SQL database structure is of significance for the integrated solution addressing product environmental performance evaluations.

Contribution to product development methodology

Beneficial with the outcomes of sustainable production support toolbox, a LCA oriented product development methodology is proposed, which specifies the functions and role of each LCA tool in the product development process. This methodology systematically addresses the research gap that there has not been an effective approach to integrate LCA technologies throughout the entire product development process. Moreover, within the context of sustainable production, the attributes, compulsory and voluntary schemes of the EU regulations and directives are discussed, and integrated into the propped methodology, proving the methodology is a holistic approach to support sustainable product development.

Contribution to product sustainability enhancement

The two LCA practices demonstrate two different application scenarios of LCA within the context of sustainable production. Using LCA to develop the sustainable flooring product proves that the LCA results can be used as benchmarking values in iterations for design optimization and materials selection, or comparison of design solutions. Assessing the environmental performance of shampoo product with LCA identifies the pollution root of manufacturing process, which would be helpful for companies to create strategies to reduce emissions and improve resource efficiency at the production level, additionally, the data of shampoo product is directly from the manufacturer, which are of significance for future study related to assessing environmental impact of shampoo products. Moreover, the analytical results are easy to be applied in elaboration of tailed improvement strategies for main activities of sustainable production, which would not only enhance product sustainability, but also enable the adopted companies to lower environmental impacts and increasing of their competitiveness with respect to other suppliers, manufacturers and any other involved stakeholders.

10.2. Limitations of this research project

The limitations of this study have been explained throughout the thesis. However, there are a few more limitations which need to be discussed and clarified, which are presented as follows.

The proposed Sustainable Production Support Toolbox including the LCA technologies, standards of environmental management system, and the EU regulations and directives, which are all updated in a regular time period, particularly, the regulations and directives usually have a variety of amendments. It is not possible to include all the latest versions of these tools in this toolbox, in order to elaborate the benefits of these regulatory rules, users are suggested to refer for the framework and rationale that are presented in the demonstrated methodologies for developing sustainable flooring product.

The proposed solution and its implementing LCA service platform has been designed considering the emerging business and technology demands. In order to extend this solution into a practical level, some points at the micro level are still needed to discuss, e.g. clarifying product process boundary; designing allocation rules for input and out flow associated with resources utilisation and emission. At the business level, improving the reliability and credibility of the calculation results is a challenge to address. For example, the finalised results possibly vary with the same type products among different batches, under this circumstance, how to address the difference or convince consumers to trust the originality of those figures, which are required to discuss for implement practical solutions.

The LCA service platform is developed and tested under a research level, and more tests reflecting the real application scenario are required to conduct in order to improve the efficiency and performance of this platform. The possible tests include: business users record and input data, and import and export the LCI data; consumer users retrieve product data or calculation results, and implement the results comparison.

For the LCA of shampoo product, analysis of sub-sectors is not implemented in this study due to the data limitations to provide more accurate figures describing of the impacts from the whole shampoo industry. Moreover, different recycling targets for various packaging wastes have been adopted in this practice, which are used to model environmental impacts of packaging recycling performance. The adopted recycling level range from 2.7% up to 46.6% varying on the material type, and these figures are provided by the UK DEFRA in the 2016 report 'UK Statistics on Waste'. However, the methodology of obtaining these figures are not validated in this study as it is not disclosed, and it is challengeable if sufficient capacities are applied to recycle or reuse those wastes.

10.3. Future research

According to the nature of this research, a number of ideas for future research work is of significance for introducing. The following suggestions are created with the aim of improving the relevant works at methodological and practical level.

Currently, other types of data sources cannot be integrated into the system because the heterogeneity issue. Some legacy systems which involve other types of databases or existing queries are widely used in industries. Therefore, it is worth to further develop LCI management system in order to enable it to integrate other types of data sources. A possible method is that data in other data models are interpreted into relations. Then re-programme schemas for these relations, and store them into the meta-database with additional information such as whether the relation is an existing data in other data model, and information describing the access method.

There is an increasing demand to apply commercial cloud platform to deliver this type of software/application based service, because this commercial cloud platform performs a more stable operating environment with reasonable charges. It is meaningful to explore how to deploy this LCA service related system and applications in the commercial cloud platforms, in order to achieve the scalability of these developed LCA services.

This study uses the indicators of ReCiPe methodology to demonstrate how the solution works within the context of transition towards a resource-efficient economy and sustainable production, but the proposed technical elements also have the ability to cope with any other chosen indicators in the future, such as those suggested within the PEF initiative. Furthermore, the developed solution aims to achieve multi-objective evaluation that considers the economic, and social performance at the level of product life cycle, therefore, the feasible performance indicators are required to investigate.

10.4. Conclusions

This research introduces a novel integrated solution to assess product environmental performance at the level of product life cycle, value chain and consumption of individuals. This solution not only presents a new scenario addressing environmental impact evaluation, but also provides a new approach and application gathering high quality data for improving accuracy for LCA. With the analysis and interpretation of gathered data, companies can improve resource efficiency and social corporate performance at the level of raw material selection, production, distribution, and recycle phrase, in order to strengthen their competitiveness.

The implementation of the integrated solution is achieved by a LCA service platform, and the required services are provided by a set of developed software/applications. The LCA service based platform has been developed by adopting the SOA framework to demonstrate a novel solution to deliver advanced LCA service through web and mobile application platforms, which enhances the LCA service performance into a more practical level. The core function of this platform, the web based environmental impact calculation, is validated by conducting LCA on the shampoo product. The calculation results successfully prove that the designed system services meet the requirements of LCA practices.

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Appendices

Appendix 1. Part code of the Python script for extracting EcoSpold 1 datasets

```
def xml_open(path):
    items = os.listdir(path)
    new_items = []
    for f in items:
        f_name, f_suffix = os.path.splitext(f)
        if f_suffix == ".XML":
           new_items.append(f_name+f_suffix)
    return new_items
def xml_data_capture(path):
    #declare list
    a=[]
    for i in xml_open(path):
        tree = ET.ElementTree(file=i)
        root = tree.getroot()
        dataset = (root[0].attrib)
        key_dataset = {'number'}
        number = "\nnumber: " + str(dataset.get('number'))
        referenceFunction = (root[0][0][0][0].attrib)
        category = "category: " + str(referenceFunction.get('category'))
        subCategory = "subCategory: " +
        str(referenceFunction.get('subCategory'))
        name = "name: " + referenceFunction.get('name').encode("utf-8")
        CASNumber = "CASNumber: " + str(referenceFunction.get('CASNumber'))
        unit = "unit: " + str(referenceFunction.get('unit'))
        amount = "amount: " + str(referenceFunction.get('amount'))
        geography = (root[0][0][0][1].attrib)
        location = "location: " + str(geography.get('location'))
        content = "\n" + number + "\n" + category + "\n" + subCategory +
        "\n" + name + "\n" + CASNumber + "\n" + unit + "\n" + amount + "\n"
        + location
        a.append(content)
    return a
if __name__ == "__main__":
    #file_path= (r"C:\Users\dsg3wuy\Desktop\test")
    file_path= r"C:\Users\dsg3wuy\Desktop\test"
    content_list = xml_data_capture(file_path)
    with open("test.txt","a") as w:
        for content in content_list:
            w.write(content)
    print "done"
```

Appendix 2. Mapping table for data-bridging GUI application to generate EcoSpold1 file

Legends for the mapping table

- Green columns represent compulsory data elements for the LCA calculations
- Orange columns represent data types proceeded in the back end of the GUI
- Cells with square brackets indicate the value will be a constant number. For instance, '[2]' represent the value will be fixed to 2.
- A cell of a pair of round brackets, the activity is proceeded via code and not displayed to the user. For example, '(Today's date)' indicates today's date will be generated automatically for the value.
- Cells without any bracket are required to input by users, which are indicated in the right section coloured by dark blue. For instance, 'localName' is the relevant field in the EcoSpold file. It is the local name of product and needs to be input by user in the client interfaces

EcoSpold				Type	Compulsory in LCA calculation	Programme in background	Input displayed on GUI
Dataset			number	Number	ProductCode	(as file name)	
			Generator	String		[myEcoCost data bridging v1]	
			Timestamp	XML DateTime		(Today's date)	
Meta information	Process information	Reference function	datasetRelatesToProduct	Boolean		[true]	
			name	Text	ProductName		
			localName	Text		localName	local name of the product
			amount	Number(Real)	ProductAmount		
			unit	Text	ProductAmountUnit		
			category	Text	Category		
			subCategory	Text	SubCategory		
			localCategory	Text		localCategory	Local category of the product
			localSubCategory	Text		localSubCategory	Local subcategory of the product
			GeneralComment	Text	GeneralComment		
			CASNumber	String	CASNumber		
			statisticalClassification	Number (Long)	StatisticalClassification		
		Geography	location	Text	Location		
		Timeperiod	dataValidForEntirePeriod	Boolean		[ture]	
			startDate	Text		startDate	Start date
			endDate	Date		endDate	End date
		Dateset Information	type	Integer		[2]	
			impactAssessmentResult	Boolean		[false]	
			timestamp	DateTime		(Today's date)	
			version	Decimal		[2.2]	
			internalVersion	Decimal	Version		
			energyValues	Byte		[0]	
			languageCode	Text		[en]	
			localLanguageCode	Text		[de]	
	Modelling and validation	Source	Number	Integer		[231]	
			sourceType	Byte		[0]	
			firstAuthor	Text		firstAuthor	Name of user
			year	Integer		[2015]	
			title	Text		[myEcoCost]	
			placeOfPublications	Text	Location		
	Administrative information	Data entry by	Person	Integer		Person	ID of user
			qualityNetwork	Integer		[1]	
		Data generator and publication	person	Integer		(same as Person)	
			dataPublishedIn	Byte		[0]	
			referenceToPublishedSource	Integer		[231]	
			copyright	Boolean		[true]	
			companyCode	Text	CompanyCode		
			countryCode	Text	Location		
		Person	number	Integer		(same as Person)	
			name	Text		(same as first author)	
			address	Text	CompanyAddress		
			telephone	Text		telephone	Telephone number
Flow data		Exchange	number	Integer	FlowId		
			category	Text	Category EFDR		
			subcategory	Text	SubCategory EFDR	**LEGEND**	
			CASnumber	String	CASNumber EFDR	**(notes)**	
			name	Text	FlowName EFDR	**[fixed value]**	
			location	Text	Location	**Relevant field in EcoSpold**	
			unit	Text	FlowUnit EFDR		
			meanvalue	Single	FlowValue		
			GeneralComment	Text			
			inputGroup	Number		[4]	
			outputGroup	Number		(4 or 0)	

Appendix 3. Part code for showing the JNI to implement the HPCL

```
package org.openlca.eigen;

import java.io.BufferedReader;
import java.io.InputStreamReader;

import org.openlca.core.database.IDatabase;
import org.openlca.core.database.mysql.MySQLDatabase;
import org.openlca.core.math.DataStructures;
import org.openlca.core.math.IMatrixSolver;
import org.openlca.core.math.LcaCalculator;
import org.openlca.core.matrix.Inventory;
import org.openlca.core.matrix.InventoryMatrix;
import org.openlca.core.matrix.cache.MatrixCache;
import org.openlca.core.model.ProductSystem;
import org.openlca.core.results.FullResult;
import org.openlca.eigen.solvers.DenseSolver;

public class Benchmark {

  public static void main(String[] args) {
    TestSession.loadLib();

    IMatrixSolver solver = new DenseSolver();

    int runs = 1;
    // IDatabase db = new
    // MySQLDatabase("jdbc:mysql://localhost:3306/openlca",
    // "root", "");
    IDatabase db = new MySQLDatabase(
        "jdbc:mysql://localhost:3306/openlca_ei3_pre", "root", "");
    MatrixCache cache = MatrixCache.createEager(db);
    ProductSystem system = db.createDao(ProductSystem.class).getForId(
        654886);
    Inventory inventory = DataStructures.createInventory(system, cache);
    InventoryMatrix matrix = inventory.createMatrix(solver
        .getMatrixFactory());
    LcaCalculator calculator = new LcaCalculator(solver, matrix);

    System.out.println("Inventory ready. Type enter to start!");
    try {
      InputStreamReader r = new InputStreamReader(System.in);
      BufferedReader reader = new BufferedReader(r);
      reader.readLine();
    } catch (Exception e) {
      e.printStackTrace();
    }

    System.out.println("Run new benchmark");
    System.out.println("run \t t(quick)[ms] \t t(analyse)[ms] \t mem[MB]");
    FullResult result = null;
    for (int run = 1; run <= runs; run++) {
      result = null;
      System.gc();
      long start = System.currentTimeMillis();
      calculator.calculateSimple();
      long quick = System.currentTimeMillis() - start;
      System.gc();
      start = System.currentTimeMillis();
      result = calculator.calculateFull();
      long analysis = System.currentTimeMillis() - start;
      Runtime r = Runtime.getRuntime();
      double mem = (r.totalMemory() - r.freeMemory()) / (1024 * 1024);
      System.out.printf("%d \t %d \t %d \t %.2f \n", run, quick,
          analysis, mem);
    }
```

Appendix 4. An example for showing the FlowExport API

```
class FlowExport extends AbstractExport {

	@Override
	protected void doIt(CsvListWriter writer, IDatabase database) throws Exception {
		log.trace("write flows");
		FlowDao dao = new FlowDao(database);
		List<Flow> flows = dao.getAll();
		for (Flow flow : flows) {
			Object[] line = createLine(flow);
			writer.write(line);
		}
		log.trace("{} flows written", flows.size());
	}

	private Object[] createLine(Flow flow) {
		Object[] line = new Object[8];
		line[0] = flow.getRefId();
		line[1] = flow.getName();
		line[2] = flow.getDescription();
		if (flow.getCategory() != null)
			line[3] = flow.getCategory().getRefId();
		if (flow.getFlowType() != null)
			line[4] = flow.getFlowType().name();
		line[5] = flow.getCasNumber();
		line[6] = flow.getFormula();
		if (flow.getReferenceFlowProperty() != null)
			line[7] = flow.getReferenceFlowProperty().getRefId();
		return line;
	}

}
```

Appendix 5. An example for showing RefDataExport API

```java
@Override
public void run() {
        try {
                if (!dir.exists())
                        dir.mkdirs();
                export("locations.csv", new LocationExport());
                export("categories.csv", new CategoryExport());
                export("units.csv", new UnitExport());
                export("unit_groups.csv", new UnitGroupExport());
                export("flow_properties.csv", new FlowPropertyExport());
                export("flows.csv", new FlowExport());
                export("flow_property_factors.csv", new FlowPropertyFactorExport());
                export("lcia_methods.csv", new ImpactMethodExport());
                export("lcia_categories.csv", new ImpactCategoryExport());
                export("lcia_factors.csv", new ImpactFactorExport());
                export("nw_sets.csv", new NwSetExport());
                export("nw_set_factors.csv", new NwSetFactorExport());
                exportMappingFiles();
        } catch (Exception e) {
                log.error("Reference data export failed", e);
        }
}

private void export(String fileName, AbstractExport export) {
        File file = new File(dir, fileName);
        if (file.exists()) {
                log.warn("the file already exists; did not changed it");
        } else {
                export.run(file, database);
        }
}
```

Appendix 6. ERD for the database of the web based product environmental performance evaluation system